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ABSTRACT

This booklet is one of the booklets in the "Understanding the Atom Series" published by the U. S. Atomic Energy Commission for high school science teachers and their students. The discovery of the neutrino and the research involving this important elementary particle of matter is discussed. The introductory section reviews topics basic to the understanding of neutrino research: the electron, isotopes, wave character of the electron, spin, the neutron, transformation of particles, the photon, electromagnetic properties, interactions, and relativistic mass. The major portion of the discussion describes how the existence of neutrinos was confirmed, including such concepts as the laws of conservation, the paradox of the energy-momentum balance, particle-antiparticle annihilation, and other topics. Numerous photographs and diagrams are utilized and a list of suggested references is included. (PR)

The Elusive Neutrino

by Jeremy Bernstein

ATOMIC ENERGY COMMISSION/Division of Technical Information

The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

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THE ELUSIVE NEUTRINO

by Jeremy Bernstein

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THE ELUSIVE NEUTRINO

by Jeremy Bernstein

INTRODUCTION

If a physicist were asked, "What is a neutrino?", he would reply that it is an *elementary particle*, which conjures up the image of a tiny billiard ball. The neutrino is nothing like this, but the conception of an elementary particle has grown out of experience and language appropriate to billiard balls.

A billiard ball has size, mass (or weight), and perhaps electric charge.* If set in motion it has momentum and kinetic energy.† At rest it has an energy given by Einstein's celebrated equation $E = mc^2$.

Size, mass, and electric charge are macroscopic properties of matter—one can ascribe these properties to any unit of matter, even the tiniest units such as the neutrino as well as the largest such as galaxies. As we shall see later there are other properties, such as spin, wavelength, helicity, lepton number, etc., which exhibit themselves most clearly in the subatomic domain of the elementary particles and which are not useful in the description of real billiard balls.

*A billiard ball also has color, but this is not a property that one can ascribe to elementary particles, which can't even be seen with the naked eye. Color is an example of a macroscopic property—a property that is manifested through the behavior of millions of atoms acting in concert. Other macroscopic properties are taste, smell, and temperature.

†Kinetic energy is the energy associated with the motion of material bodies.

Greek Origins

The modern view of an elementary particle did not arise full grown like Venus in the seashell. It has a history extending back to the Greeks. The Greek atomists, notably Democritus and his school, came upon the notion of elementary particles by pure reason—a dangerous path in science for as often as not the pure reason of today is the scientific nonsense of tomorrow.* They reasoned that matter could not be subdivided without limit. If one continued breaking a twig, one would eventually come to an elemental twig, which could not be subdivided further. These elemental units of matter were called atoms (atom means indivisible in Greek) and were the building blocks out of which ordinary matter was constructed.

There was in the Greek atomic idea something that has been with us ever since and one which is crucial to modern science: The regularities in our everyday experience can be explained by postulating the existence of a new domain of phenomena. These atoms are simpler than the things we see around us and, although not directly observable, control the behavior of the things that we *do* see. For example, we explain that an object is hot because it is composed of atoms in motion and the energy of this motion produces the effect that we call heat.

19th Century Revival

For nearly 2000 years the idea of the atom lay dormant and was not revived in its present form until the 19th century. The impetus for the revival was chemists, who observed that chemical compounds always contain their constituents in constant proportions by weight however small the sample. For example, if you hook tennis balls and golf balls together, pairing always one tennis and one golf ball, then any sample of these molecules will contain, by weight, the same ratio of tennis to golf ball weights. The new atomists like John Dalton must have had some picture like this in mind to explain the law of constant proportions. Many celebrated scientists thought that this was pure nonsense until Einstein, in 1905, explained the Brownian motion—the apparently random motion of tiny objects suspended in a colloidal liquid—as being the effect of the constant bombardment these objects suffered from the molecules or atoms in the liquid. This was the first time since the Greeks that invisible atoms were used to explain a complex visible phenomenon in physics.

*They also argued, for example, that "nature abhors a vacuum", but intergalactic space is nearly pure vacuum!

Albert Einstein in 1905.

The Electron

It was also at about this time that the elementary particles began making their appearance. Electrons* were ejected from metal plates when they were heated red hot; this is, of course, what happens in a vacuum tube where electrons are boiled off a metal plate in the tube and swept through a potential drop to a second metal plate. Electrons were also ejected from a metal plate when light was shown on it. This photoelectric effect was explained by Einstein, also in 1905, by assuming that light came in bundles of energy, called photons or quanta, which were more energetic the more violet the light. Electrons were also observed to be emitted spontaneously in the decay of many radioactive isotopes.† What was *not* observed, at the time, is that the emission of a beta ray, as the electrons were called, was always accompanied by the emission of an invisible partner which, in fact, was none other than our neutrino. Why it took so long for this elusive partner to be identified will be discussed later.

Like a billiard ball an electron has a rest mass, but in this case it is so small—9.108×10^{-28} gram—that it is difficult to imagine. For practical purposes physicists do not discuss the rest mass, m_0, but rather the rest energy, m_0c^2, where c is the velocity of light—$c = 2.997925 \times 10^{10}$ centimeters per second. In elementary particle physics the rest energy is usually measured in electron volts or millions of electron volts. One million electron volts (1 MeV) equals about 1.6×10^{-6} erg. An erg is not much energy and a million electron volts is a lot less. In these units an electron has a rest energy of about 0.511 MeV. (It also has a charge whose exact value need not concern us here.)

However, in most other respects, the electron is not at all like a billiard ball. In the first place the electron has a *spin*. This is sometimes described as the angular momentum the electron would have at rest, just as if it were spinning, like a top, around an axis. This is a crude way of visualizing an intrinsically novel feature of the electron. For our purposes, we can simply say that, in addition to the angular momentum an electron acquires due to its motion, there is an extra angular

*An electron is an elementary particle with a negative electrical charge and a mass $\frac{1}{1837}$ that of a proton. Electrons surround the positively charged nucleus and determine the chemical properties of the atom.

†An isotope is an atom of an element with the same atomic number but with a different weight. A radioactive isotope, or radioisotope, is one that decays or disintegrates spontaneously, emitting electromagnetic radiation and other particles.

momentum that is not present for a classical particle* like a billiard ball.

Secondly the electron exhibits wave-like behavior in many circumstances. If a beam of electrons is focussed on a suitable diffraction grating—one where the divisions are of atomic dimensions—a pattern is produced similar to that of diffracted light. This very striking feature of the electron, and of all elementary particles, was quite unexpected by the physicists who found it in the 1920s.

Isotopes

At this same time it was recognized that since hydrogen was the lightest element, ionized hydrogen† must be some sort of fundamental unit of matter. This idea can be traced to the English chemist William Prout, who, in 1815, argued that matter must be built of hydrogen-like units. This idea fell out of favor when it turned out that the heavy elements did not weigh an amount that was a simple multiple of the hydrogen atom. This was resolved with the discovery of isotopes, which have the same chemical properties as the element itself but different weights. It was then clear that if a random sample of an element and its isotopes were weighed, the observed weight need not be an integer multiple of the weight of the hydrogen atom.

Moreover, when two units of matter are fused to form a third, there is always a loss of energy in the process. This energy is emitted as radiation. In this case the sum of the weights of the separate parts is less than the weight of the fused unit.

The discovery of isotopes raised an intriguing question. The chemical properties of an element are ultimately determined by the number of electrons it contains. Because the chemical atom is electrically neutral, this number must be equal to the number of protons since the proton has a positive charge and the electron a negative charge. Since an isotope has the same number of protons as the element itself, why does it weigh more?

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*It is a classical particle because its motion can be calculated using Isaac Newton's classical mechanics. These mechanics cannot be used for atomic particles or subatomic particles. For these motions one must use wave or quantum mechanics. Even the motion of a billiard ball, according to modern ideas, will also involve quantum mechanical effects but these are negligibly small.

†Hydrogen that has had its electron removed; this unit of matter is also called the proton. Ionization is the process of adding or removing electrons from atoms or molecules.

It was here that the physicists made an understandable mistake. They argued that since electrons appeared to come out of those isotopes that beta decay, there must have been electrons inside these elements in the first place. Thus, the additional weight is supplied by additional protons with electrons attached to them to make the combination electrically neutral.

One can give two very strong theoretical arguments as to why this picture fails. (In giving these arguments I shall not quite follow the historical order and therefore they appear much more convincing than they would have to a physicist in the late 1920s when so much less was known.)

Wave Character of the Electron

The first of these arguments makes use of the wave character of the electron. As had first been conjectured (in his Ph.D thesis!) by the French physicist Louis de Broglie,* the wavelength of the electron is simply related to its momentum. If we call the momentum p, where, at least for speeds small with respect to that of light, $p = mv$, then the so-called de Broglie or electron wavelength is given by the formula

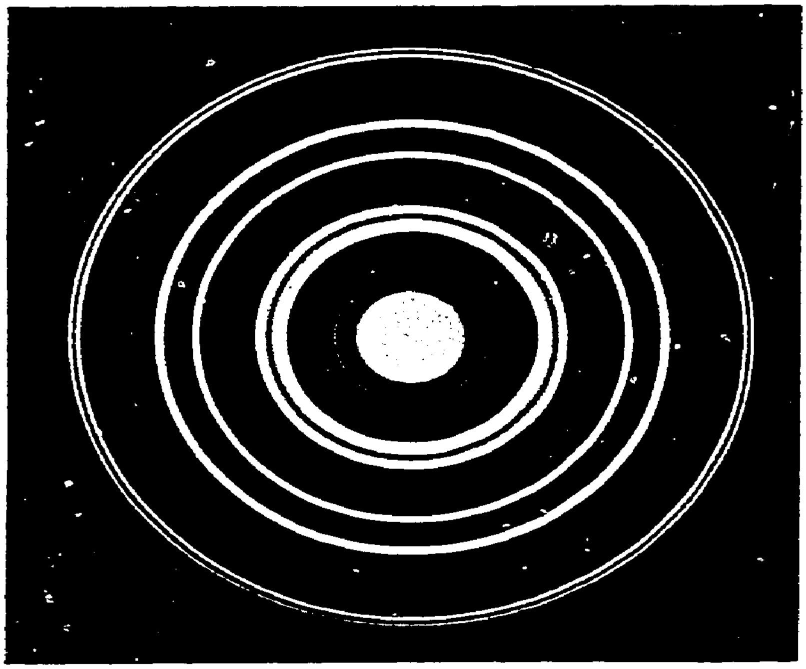
$$\lambda = \frac{h}{p}$$

Here λ is the wavelength and h is Planck's constant.† (From this formula you can see that h has dimensions of *energy* × *time* and if we choose MeV as our energy scale then experiment shows that $h = 4.1356 \times 10^{-21}$ MeV-sec.) Now we can ask and answer the following question: Since a typical nucleus has a radius of about 10^{-13} centimeter, how much energy will an electron have if we confine it to the nucleus? In other words, what is the energy of an electron whose wavelength is about 10^{-13} cm? We will not give any of the arithmetical details except to note that since the kinetic energy of an electron is related to its momentum by the formula

$$E = \frac{1}{2}\frac{p^2}{m}$$

*De Broglie received the Nobel Prize in 1929 for discovering the wave nature of electrons.

†Max Planck, a German physicist, received the Nobel Prize in 1918 for his hypothesis that all radiation was emitted in units or quanta.



Wave properties of particles. The interference pattern was produced by electrons shot through a thin foil. No electron, of course really moved along a wavy path, but the wavelike distribution of electrons is described by mathematics of waves, and the alternate bright and dark lines in the photograph are similar to effects of intereference phenomena in water waves or in light.

the de Broglie wavelength can be written in terms of the energy in the form

$$\lambda = \frac{h}{\sqrt{2mE}}$$

so that the energy can be easily computed. It turns out that this energy would have to be about 10^4 MeV.

The beta rays (electrons) that emerge from nuclei rarely have energies larger than about 10 MeV; this would be totally incomprehensible if there were electrons in the nucleus with energies of thousands of MeV. (The heavy nuclei have radii that are more nearly 10^{-12} cm than 10^{-13} cm. Even so, this argument shows that any electron inside would have a kinetic energy of several hundred MeV, which is quite unacceptable.)

Spin

The second argument depends on spin, or intrinsic angular momentum, which we discussed earlier. It is possible to measure the spins of nuclei as well as the elementary particles. Let us take a

clear-cut case. The proton and the electron each have a spin of ½.*
Moreover, there is an isotope of hydrogen that weighs about twice as much as the proton. According to the old-fashioned picture this nucleus would consist of three particles—2 protons and 1 electron—each of which has a spin of ½.

According to this picture, the spin of this heavy hydrogen,† or deuterium as it is usually called, would have to have a spin that is a half odd integer, i.e., ½, 3/2, 5/2, etc. It is not possible to add up the spins of three particles that have spin ½ and get something that has an integer spin. (This holds true even if we take into account the fact that these particles can have orbital angular momentum as well as spin.) However, experiments show beyond the shadow of any doubt that the deuteron *has* spin. Hence, once again, we cannot have electrons in the nucleus.

The Neutron

Happily, just when the physicists of the early 1930s were beginning to wrestle with these paradoxes they turned out to be totally irrelevant. In particular, in 1932, the English physicist James Chadwick "discovered"‡ the neutron. In due time it was shown that the neutron had all the properties needed to replace the proton–electron combination as the neutral constituent of the nucleus.

The neutron has a rest energy of 939.5 MeV as opposed to the proton's rest energy of 938.2 MeV. Because of its mass we do not have the paradox, discussed above, of being forced to give the neutron impossibly large kinetic energies in order to confine it to the nucleus. (A look at the formulae on the previous pages will convince the reader that the same argument leads to a prediction that neutrons have energies of only some tens of MeV's in the nucleus.) In order to escape the spin paradox one simply attributes the same spin to the neutron as to the proton, namely spin ½; this property has been confirmed by direct experiment.

*We give the spins here in units of $\hbar = h/2\pi$. You can see that h also has dimensions of angular momentum. The spin is most simply expressed in these $\hbar$ units.

†Heavy hydrogen is an isotope whose nucleus, called the deuteron, contains one neutron and one proton, which makes it twice as heavy as ordinary hydrogen, which has only a single proton.

‡Many physicists were sure that there must be a particle like the neutron, but it was Chadwick who correctly interpreted the key experiments and received the Nobel Prize in 1935 for this work.


J. Chadwick

Transformation of Particles

However, we are still left with the original question: If electrons emerge when nuclei disintegrate and, if they are not in the nucleus to begin with, where do they come from?

To answer the question we must reconsider the idea that we inherited from the Greeks: An elementary particle is an indivisible entity or atom. From an experimental point of view to say that something is "indivisible" really means that no procedure has been envisioned for dividing it. It is almost impossible to imagine what it would mean to say that something is indivisible in principle. *All* elementary particles are divisible in the sense that if A stands for such a particle then one can always find a reaction of the form $A + B \rightarrow C + D$, where B, C, and D are particles distinct from A.

For example, in the "photodisintegration" of the deuteron

$$\gamma + D \rightarrow n + p$$

where γ stands for a photon (a light quantum),
D for the deuteron,
n for the neutron, and
p for the proton.

we can say that the light quantum splits the deuterium nucleus or, if we want to be perverse, we can say that the deuteron splits up the light quantum into a neutron and a proton. This is one example among hundreds of the fact that elementary particles can always be transformed, or split, or divided into other particles.

We must, however, distinguish between two cases. On the one hand most particles are intrinsically unstable and break up spontaneously into new particles. On the other there are the stable particles that can only be divided by introducing an outside force. An example of an unstable particle is the neutron, which breaks up, on the average, in about a thousand seconds. (We shall come back later to discuss in detail the products into which the neutron breaks up.)

However the proton is stable against spontaneous decay. Hence we can say that the proton, like the electron and photon, is stable but divisible.

The point of this circumnavigation of our question—Where do the decay electrons come from if they are not originally in the nucleus?—is to make clear that this is a special case of the general proposition that elementary particles, and nuclei as well, can be transformed into each other. This is not a paradox, but rather a fact of

life. We can say that what we call the neutron is a very complex system that is constantly transforming itself into its constituent parts and then transforming itself back again.

Some of these transformations are what the modern physicist calls "virtual" by which he means they reverse themselves before they can be detected directly, and some are "real", which means that they do not violate any laws and can take place as genuine observable physical transformations. The decay of the radioactive elements, the neutron included, is an example of a real transition. The nucleus transforms itself into its decay products and these are observable in the laboratory.

The decay products are only present virtually before the decay just as a painting is not actually present on the empty canvas until the painter creates it from the virtual paintings that exist in his mind.

Well then, where are we? We began with the Greek concept of an atom as the ultimate indivisible unit of matter and we have shown that this is not exactly the modern idea of an atom. The contemporary concept is of a complex structure with an outer layer of electrons that are responsible for the atom's chemical properties and an interior nucleus that is made up of protons and neutrons. The size of the interior ranges between about 10^{-13} cm for the light nuclei to about 10^{-12} cm for the heavy ones. The electron in the hydrogen atom is typically at a distance of 10^{-9} cm from the center of the atom.

The neutrons and protons are also complex structures that can be broken up and sometimes, as in the case of the free neutron, break up spontaneously. Up to this point the players in our game have included the photon, which is the quantum of light, the electron, which is the lightest charged particle, and the neutron and proton out of which nuclei are built. We shall have occasion to introduce several new players in the remainder of this booklet.

JUST GIVE THE NEWS

Since this is not a required science text we can indulge in the luxury of being unconventional. Instead of building up our subject bit by bit we shall give the reader a general idea of what the neutrino is like. This chapter will be like a map of a strange land that we intend to visit, whose mountains, valleys, lakes, and towns will eventually become familiar to us, but which, for the moment, rest in obscurity. There is a certain pleasure in looking at such a map in order to get a feeling for what lies ahead. As good a place as any to start is with John Updike's poem in which there are both truth and poetry.

COSMIC GALL

by John Updike

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
*It wonderful; I call it crass.**

Aside from Mr. Updike's reservations about the good manners of the neutrino, the most significant themes of the poem are that the

density of neutrinos here on the earth is enormous and in our daily experience we are completely unaware of them.

The poem was inspired by an article in *American Scientist*, written by the physicists M. A. Ruderman and A. H. Rosenfeld that says, "Every second, hundreds of billions of these neutrinos pass through each square inch of our bodies, coming from above during the day and from below at night, when the sun is shining on the other side of the earth!" The sun is an enormous neutrino factory, which we will discuss later, and the neutrinos that it produces proceed tranquilly through the earth just as if it were not there at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall . . .

How can this be? Let's put the question slightly differently. What mechanism acts, in general, to stop particles once they have been set in motion? Clearly, the answer is a force, since a particle will only decelerate if a force can be brought to bear on it.

The fact that the solar neutrino penetrates the earth from pole to pole without stopping indicates that it cannot be a conventional charged particle, since they are readily decelerated by an electrostatic force. A few feet of lead will stop the most energetic electrons produced by the high-energy electron accelerators of the type found at Stanford, or Harvard–M.I.T., or Cornell.* The same amount of lead is essentially invisible to the neutrino. As far as experimental physicists can tell, Mr. Updike's statement that "They have no charge . . ." is quite correct.† However, this is not sufficient to explain their penetrating power. The photon also has no charge, but a few feet of lead will stop photons nearly as well as it will stop electrons. (Here, Mr. Updike's poetry has got the best of him. "Or photons through a sheet of glass" as an analogy to neutrinos may be sufficiently accurate for purposes of poetry, but it is not scientifically correct. It is impossible to get a sunburn through a closed glass window and this is because glass stops ultraviolet photons. A similar glass window has no effect on neutrinos.) The difference is that photons, while electrically neutral, interact electromagnetically, while neutrinos, at least in first approximation, do

*See *Accelerators*, a companion booklet in this series.

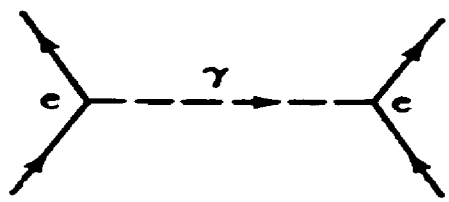
†The more precise measurements of the neutrino charge depend on arguments involving the conservation of electric charge to which we return near the end of the booklet.

not. This last statement no doubt appears obscure and confusing, but it is so important to our understanding of the subject that it behooves us to look at it more carefully.

The Photon

The photon plays a dual role in nature. On the one hand it is the particle of light—the light quantum.* Every light beam is composed of photons. On the other hand the photon acts, and this is the more subtle point, as the transmitter of the electromagnetic force.

For example, suppose there are two electrons side by side. We know that they will repel each other since they possess like charges. This is quite odd since it seems to mean that two objects which are separated in space can influence one another without touching. This is something that physicists used to call *Action at a Distance*. However, if our present theoretical ideas are sound, then the two electrons influence each other by exchanging photons in a little game of catch. (Below I have drawn the Feynman diagram† of this process.



The heavy lines are the electrons and the dotted line is the photon being exchanged between them. In reading such a diagram one imagines the electrons moving toward the top of the page and exchanging a photon, which affects their motion. In order for this little game to work the photons must be able to attach themselves to charged particles like the electron; this ability is what we meant a little earlier by the ability of photons to interact electromagnetically.

At the point of attachment I have put a letter e. This is called a "coupling constant"—a pure number that measures the strength of the attachment. It turns out that in suitable dimensionless units

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*In the 1920s the American physicist Arthur Compton showed by direct experiment that in collisions with electrons the photon obeys the same conservation laws of energy and momentum as do billiard balls when they collide with each other, hence confirming the particle aspect of the photon. Compton received the Nobel Prize in 1927 for this research.

†In 1947 Richard Feynman, an American physicist at the California Institute of Technology, invented the quantitative method of using such diagrams to compute in detail the forces acting between particles. Feynman received the Nobel Prize in 1965 for research in quantum electrodynamics.

$e^2 \simeq 1/137$. This number takes on more meaning if we also note that in the same units the strongest force in physics—the nuclear force that holds neutrons and protons in the nucleus—is characterized by a coupling constant f such that $f^2 \simeq 1$. Since this is true and since neutrinos penetrate the earth as if it were not there, we can conclude that the neutrino does not couple to charged particles with the strength e, nor, afortiori, does it couple to neutrons and protons with the strength f.

Electromagnetic Properties

Roughly speaking, the neutrino has neither electromagnetic nor nuclear interactions. The neutrino's interaction with matter is so weak (or, conversely, its ability to penetrate matter is so great) that with moderate energy it can penetrate about 3500 light-years of lead before it has a single interaction with the lead nuclei! In other words, the neutrino has only "weak interactions".

Before explaining this I would like to comment on the neutrino's electromagnetic properties so that we do not have to hedge with phrases like "roughly speaking". The neutrino is electrically neutral, i.e., it has no net electric charge. This does not mean that it cannot have a distribution of positive and negative charges that cancel each other out. This is certainly the case with neutral elementary particles in general. These elementary particles are constantly disassociating themselves virtually into other particles. A neutral particle can disassociate itself into two particles of equal and opposite charge and thereby acquire a distribution of charge.

For the neutron, this is a very important effect since the virtual disassociations take place by means of the strong couplings characterized by the large coupling constant f. The neutron's charge structure is just what is measured in the beautiful experiments done at Stanford, and elsewhere, in which the details of the neutron's electromagnetic structure are explored by bouncing energetic electrons off neutrons.

However, the neutrino doesn't have any strong couplings. Therefore, these virtual disassociations are extremely unlikely since they take place only by means of the tiny weak interaction. Up to now, the neutrino's charge structure has been unobservable.* For our purposes we can speak of the neutrino as if it had no electromagnetic properties, which is quite true "roughly speaking".

*When we describe some of the laboratory experiments that have been done on the neutrino we shall indicate how it might in principle be observed.

Interactions

To resume where we left off, we had just noted that the neutrino's extraordinary penetrating power can be "explained" by saying that the neutrino has only weak interactions. This explanation seems like a simple restatement of the facts without much additional content. However, the weak force that acts on the neutrino also shows up elsewhere. For example, this interaction causes particles like the neutron to decay. We now know that there are at least four kinds of fundamental interactions in nature: (1) the strong interaction that holds nuclei together, (2) the electromagnetic interaction that holds electrons to nuclei and is thus responsible for chemical reactions, (3) the weak interaction that causes many nuclei and elementary particles to decay, and (4) the gravitational interaction.

The gravitational force acting between two electrons in an atom is negligible compared to the electrical forces that act between them. In terms of coupling constants, we can characterize the pure number, g, that measures the weak force by something like $g^2 \simeq 10^{-5}$ as compared to $f^2 \simeq 1$. The weak force is thus approximately 100,000 times weaker than the strong force and something like 1000 times weaker than the electromagnetic force. (The square of the gravitational constant is 10^{-39}.)

Mass

We have now dealt with most of the properties of the neutrino mentioned in the poem. (The reader can appreciate that Mr. Updike's statement about neutrinos—"And do not interact at all . . ."—is a bit of poetic license. "And do not interact a lot . . ." is better science but worse poetry.) What about the curious phrase "and have no mass"? It would seem impossible for a particle to have energy but no mass. In fact the classical formula for the kinetic energy of a particle of mass m moving with a velocity v is

$$E = \frac{1}{2} mv^2$$

If m is equal to zero in the equation then the particle has no kinetic energy. However, in 1905, Einstein showed that this formula could only be correct for very slow-moving particles. All massive particles have an energy (in addition to their kinetic energy) called the rest energy since it is possessed by particles at rest. The rest energy is given by Einstein's celebrated formula

$$E_{rest} = m_0c^2$$

This is a very substantial amount of energy even for particles of moderate mass since c, the velocity of light, is so huge.

Pre-Einstein physicists never noticed that this energy was floating around since to make use of it one must be able to transform matter from one state to another in which there is less mass. If we start with an elementary particle A, which has a mass m_A, and if we can cause this particle to transform into other particles, B, C, D, etc., whose combined masses are less than the mass of A, then the difference

$$E = [m_A - (m_B + m_C + m_D + \ldots)]c^2$$

will appear as available kinetic energy that is shared among the particles B, C, D, etc. that emerge after the reaction. This sort of transformation is just what happens when a particle like the neutron decays spontaneously. The decay products, or daughter* particles, take off the kinetic energy that is made available to them because they are less massive than the particle that decays.

Thus the classical formula for the energy of a particle is wrong at both ends of the velocity scale. It ignores the rest energy of a particle and it has the wrong mathematical form when the velocity is too large.† We can't give a derivation of the correct relativistic energy formula here, but there are several excellent books on the theory to which we refer the reader on page 74. We shall just write it down without apology and remark that it exhibits all the properties that we would like it to have.

$$E = \frac{m_0c^2}{\sqrt{1 - \frac{v^2}{c^2}}} = \sqrt{m_0^2c^4 + p^2c^2}$$

In these equivalent expressions of the relativistic energy the symbols have the following meanings:

m_0 is the rest mass of the particle. [A particle in motion has a mass given by the formula $(m_0/\sqrt{1 - v^2/c^2})$ which states that the faster a particle goes the more inertia it has.]

*A daughter is a nuclide formed by the radioactive decay of another nuclide, which in this context is called a parent.

†When one speaks of large or small velocities one always means in comparison to c—the velocity of light—which Einstein showed was the maximum possible velocity a particle could have.

where c is, as usual, the velocity of light,

v is the speed of the particle, and

p is the "relativistic momentum" of the particle, which is given by the expression

$$p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

(For small velocities—that is when $v/c \ll 1$—this formula for p reduces to our old friend $p = m_0 v$. As an algebraically inclined reader can check in three minutes, it is the special form of p that makes the two expressions for E, the energy, equal to each other.) It is easy to show that for small velocities the expression for the energy becomes

$$E \simeq m_0 c^2 + \frac{1}{2} m_0 v^2$$

which is the classical kinetic energy plus the rest energy.

We can now see what it would mean for a particle to have energy but not mass—something that makes no sense at all in classical pre-Einstein physics. The simplest way to begin the discussion is to set $m_0 = 0$ in the expression

$$E = \sqrt{p^2 c^2 + m_0^2 c^4}$$

Thus for a mass-less particle

$$E = pc$$

or the energy is simply proportional to the momentum of the particle. If we set $m_0 = 0$ in the other expression for E

$$E = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

we seem to run into serious trouble since, evidently, the numerator vanishes, and it might then appear that the energy also vanishes. This contradicts the conclusion that for a mass-less particle the energy is proportional to the momentum.

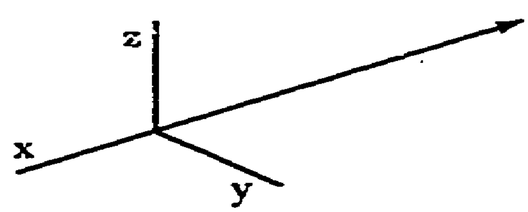
However, we have one possible trick up our sleeve, and that is to make the denominator vanish as well, which will then produce an expression in which zero is divided by zero. One will again be led to the conclusion that for a mass-less particle the energy is proportional to the momentum.

To make the denominator equal to zero is simple since all we have to do is to put $v = c$. In other words if *all* zero mass particles *always* move with the velocity of light then everything becomes consistent again. The converse is also true—any particle that moves with the velocity of light must have zero mass. The photon obviously moves with the velocity of light and it is a particle with zero mass. We have gone into all this detail because, to the limits of our present experimental accuracy, the neutrino is also a particle with zero mass and hence the neutrino also moves with the speed of light!

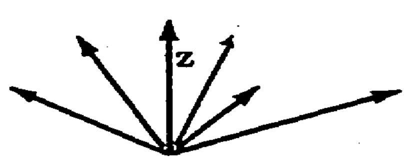
Spin

By now, the reader must feel that the neutrino is an extraordinary particle. I shall reinforce this impression by closing this chapter with yet another property of the neutrino—one that is not hinted at in Mr. Updike's fine poem.

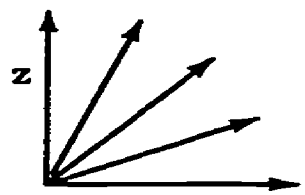
Like other particles of modern physics the neutrino has a spin. This spin, like that of the neutron, proton, and electron is just ½. Spin is a kind of angular momentum, and in classical physics angular momentum, like momentum itself or velocity, is a vector quantity, which means that "it has both magnitude and direction". A velocity is so many miles per hour toward, say, the southwest. Such a quantity is represented by an arrow in the direction of the vector and the length of the arrow is the size of the physical quantity represented by the vector.



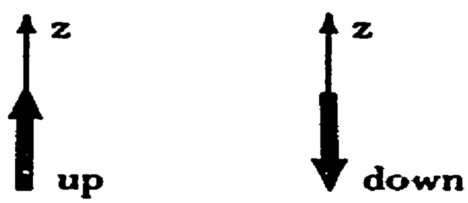
In classical physics a vector can point in any direction. The classical angular momentum vector below points at various angles with respect to an arbitrary direction, which we call the z direction.



In the quantum physics of elementary particles it turns out that the angular momentum vector cannot point in any direction once the z axis has been chosen. There is a fixed number of angles at which it is allowed to point—the number of these angles being related to the length of the vector.



For a spin ½ particle the vector representing the spin can only point in *two* directions, once a particular z axis is chosen, two directions that we can call up or down. In these pictures the heavy arrows represent the spin.



In these pictures the heavy arrows represent the spin.

This is a basic fact about spin ½ systems. This is strange enough but the neutrino is even stranger and is, with respect to the property that we are about to describe, apparently unique. The neutrino has momentum, like any other particle, and since its energy is given by the relation $E = pc$, its momentum is specified once its energy is known by the equation $p = E/c$. (The reader may once again note that the relativistic expression for the momentum

$$p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

becomes zero/zero for a zero-mass particle.) This momentum can again be represented by an arrow

Now, and this is the really incredible part, experiments show absolutely unambiguously that the spin of the neutrino always points in the

opposite direction to its momentum

The spin arrow, and the momentum arrow are always in opposite directions a fact that physicists denote with the statement that the neutrino is a particle with negative helicity. (In a later chapter I shall explain how this is known and where the term helicity came from.)

I would like to end this section with a brief remark about the neutrino and the theory of relativity. First a fact: If a particle with a non-zero mass is moving with some speed, say 310 miles an hour, we can always in principle run beside it; to us the particle would appear as if at rest. What is at rest and what is in motion depend on the reference system used.

However, and this is also a consequence of the theory of relativity, a zero-mass particle will move with the speed of light in any system. We, who are of non-zero mass, simply cannot move with the speed of light. We cannot catch up to the neutrino and we can never bring it to rest. Thus the neutrino, and the photon as well, are *relativistic* particles in the sense that we cannot even begin to describe their motion without using the theory of relativity, which applies when particles move at, or near, the speed of light. In pre-Einstein physics such a particle could not even be contemplated. Einstein's theory provides the natural and, indeed, the only language for describing the motion of neutrinos.

Experimental Method

In 1931 the Austrian theoretical physicist Wolfgang Pauli* "invented" the neutrino. I use the word invented rather than discovered because his work illustrates an important aspect of the scientific method. To most people a scientist is someone who enters a laboratory,† his mind unclouded by prejudices, and reports what he sees. Thus science appears to be an elaborate form of bird-watching and the discovery of a new particle appears to be made in a fashion something like the discovery of a new warbler.

Scientific discoveries, especially those of modern physics, are nearly the opposite of this description. All scientists enter the laboratory with prejudices. These prejudices represent the body of accepted scientific principles that were valid prior to the experiment they are performing. Most experiments in physics are aimed at a result suggested by theory. It is practically unheard of for someone to go poking around with a large expensive accelerator in the hope that something interesting may turn up. The most exciting discoveries arise when a scientist finds something that contradicts his prejudices, and it is the mark of a good scientist that he is able to produce results so reliable that he has more confidence in them than he does in his preconceptions.

Conservation Laws

In physics, we have come since the time of Newton to place a great deal of confidence in a set of theoretical ideas called *conservation laws*, which describe quantities that remain unchanged during physical processes. In all reactions energy is conserved.

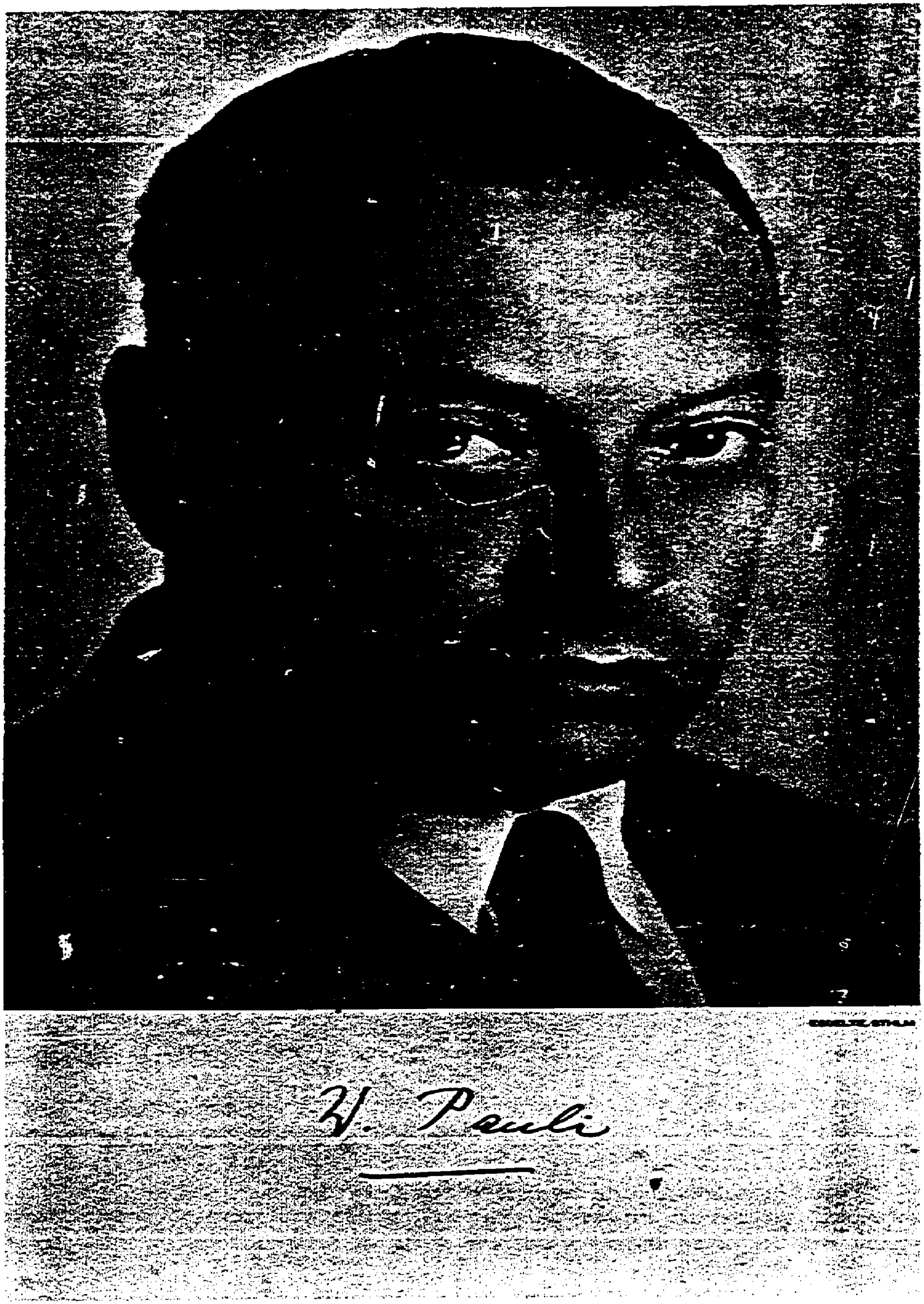
It has sometimes been argued that the conservation of energy law can never be violated since, if we find a reaction that violates it, we can say that there is an energy exchange which we have not taken into account. In familiar physical and chemical processes, we can balance energies without resorting to new forms, which is what makes the law of the conservation of energy so useful.

Quantitative Study of Radioactive Nuclei Decay

When we enter a new domain of scientific experience it is natural to assume that general principles such as the conservation of energy are

*He received the Nobel Prize in 1945 for research on atomic fission.

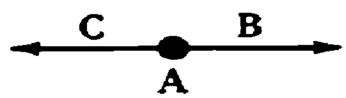
†Pauli, however, never conducted an experiment after he left school. He did all his work with paper and pencil.


W. Pauli

still valid. If we run into a contradiction then we will have learned something new. At the time of Pauli's invention, the new domain was the quantitative study of radioactive nuclear decay. These nuclei, which had been studied since the turn of the 20th century, gave off radiation of three basic types, which are called alpha, beta, and gamma rays. Alpha rays are streams of alpha particles, which consist of 2 neutrons and 2 protons, and are helium nuclei. Gamma rays are very energetic photons. Beta rays are streams of beta particles, i.e., electrons.*

With the advent of the quantum theory, or wave mechanics, in the 1920s it was possible to give a simple quantitative theory for alpha and gamma decays, which were caused by the well-understood electromagnetic interaction. The beta decays were something else; some beta rays coming from radioactive nuclei carried less energy than they should have in order to conserve energy.

To appreciate the dilemma that confronted Pauli, let us consider a "two-body decay"† of the form $A \rightarrow B + C$ where A, B, and C are particles or perhaps nuclei.



In order for this decay to occur the sum of the rest masses of B and C must be less than the rest mass of A. It is natural to assume that the conservation laws apply here. If we ignore relativistic corrections, which is a reasonable thing to do if the particles in question are heavy and slow moving, then each particle has an energy associated with it that we can write in the two equivalent forms

$$E = m_0c^2 + \frac{1}{2}m_0v^2 = m_0c^2 + \frac{p^2}{2m_0}$$

where p is the nonrelativistic momentum $p = m_0v$. Thus the conservation of energy simply says that

$$E_A = E_B + E_C$$

*Why should heavy elements emit helium nuclei and not something else? This is because the helium nucleus is extremely stable compared with other light nuclei, and for some purposes one can think of heavy nuclei as consisting of clusters of alpha particles.

† This occurs when a particle decays into two other particles.

However, we also have the conservation of momentum, which states that in a reaction of this kind in which no force is introduced into the system from the outside, the combined momentum of B and C must be equal to the momentum of A. We can always suppose that A is at rest when it decays and hence has *no* momentum. To put the matter another way, so long as A is massive and does not move with the speed of light we can always study its decay at rest. In practice, A is usually a heavy nucleus that forms part of a chunk of matter at rest in the laboratory. Thus, without any loss of generality we can suppose the momentum of B and C add up to zero, the momentum of A

$$O = p_B + p_C$$

We can represent this equation by the picture below.

$$\xleftarrow{\quad p_B \quad}\xrightarrow{\quad p_C \quad}$$

This implies that the magnitudes of the two momenta p_B and p_C are identical. The two momenta are pointing in opposite directions but they have identical magnitudes. This, together with the energy equation, enables us to draw a remarkable conclusion that led to the invention of the neutrino. We can now write the energy equation in the form

$$(m_{0A} - m_{0B} - m_{0C})c^2 = \frac{p^2}{2m_{0B}} + \frac{p^2}{2m_{0C}}$$

since E_A is just $m_0 c^2$ as A is at rest.

This equation uniquely fixes p, which is the magnitude of the common momentum of particles B and C in terms of the masses of the three particles. Thus

$$p = \sqrt{\frac{2(m_{0A} - m_{0B} - m_{0C}) \cdot m_{0B} m_{0C} \cdot c^2}{m_{0B} + m_{0C}}}$$

The crucial point is that the conservation of energy and momentum in a two-body decay is completely fixed once the masses of the particles are known. If you tell me what the masses of A, B, and C are, I can, by plugging these masses into the formula, tell you what kinetic energies B and C must have.

Paradox of the Energy—Momentum Balance

Now comes the paradox. In beta decay, one of the particles emitted is an electron. By applying electric and magnetic fields of known magnitudes one can determine the electron's energy from the trajectory that it follows in these fields.

By the time of Pauli's invention it had become clear from experiments of this type that the electron energy was *not* fixed in beta decay. A detector, which measures electron energies, placed next to a lump of beta-active material of a given kind, will reveal that the electrons do not have one single energy, but rather a range, or spectrum, of energies varying from zero kinetic energy to a certain maximum that depends upon the material in question. In a given observed beta decay, the electrons have a range of energies. In a two-body decay they would have only one unique energy.

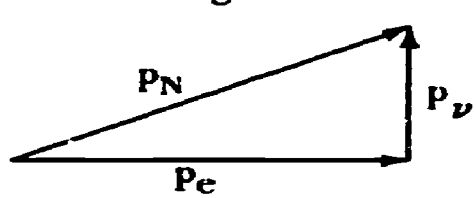
There are only two possible conclusions to be drawn from this experimental fact: Either energy and momentum are not conserved, or the decay is not two-body and there are additional particles being emitted besides the electron and the nucleus. Just prior to Pauli, some physicists including Niels Bohr, contemplated abandoning the conservation of energy and momentum in beta decay.

Why didn't they look for the additional particle, save the conservation laws, and be done with it? The trouble was that the additional particle was completely undetectable. Pauli didn't believe that nature would choose beta decay as the unique process in which to violate the conservation laws. This was a matter of scientific intuition and Pauli might well have been wrong and Bohr right, in this case, as he was in so many others. But Pauli *was* right, and the additional particle is the neutrino.

Before continuing with the development of the neutrino hypothesis we should indicate briefly how the presence of a third particle relieves the paradox of the energy—momentum balance. We can assume that the initial particle is at rest so that the momentum equation is

$$O = p_e + p_\nu + p_N$$

We have labeled the three final momenta according to the particles that carry the momentum—the electron, neutrino, and nucleus respectively. Thus there is the vector diagram



The momentum equation contains the three momenta to form a triangle but it does not fix the directions of any of the momenta. The energy equation is now

$$m_A c^2 = p_\nu c + E_e + E_N$$

where, anticipating future developments, we have put in the form for the neutrino energy that is appropriate to a zero rest-mass neutrino. From these equations we cannot conclude that the electron has one fixed energy in beta decay. The best we can do is to set limits on the electron energy. If we solve these equations the smallest total energy the electron can have is its rest energy while the largest is approximately the difference between the rest masses of the nuclei A and N, i.e.,

$$m_A c^2 - m_N c^2$$

In practice, this maximum energy ranges between 1 and 10 or 15 MeV. There is nothing in this set of conservation equations that tells at what energy we are most likely to find the electron, but at least we are no longer embarrassed by the fact that the electron energy in beta decay covers a range. The neutrino hypothesis has taken care of that.

Enrico Fermi's Little Neutral One

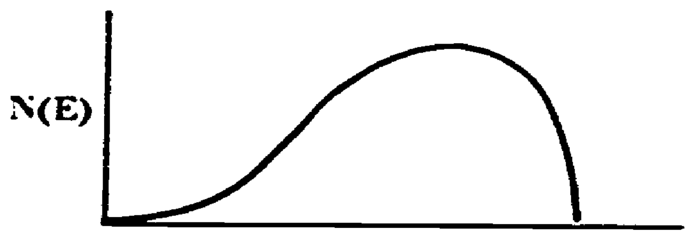
The next important figure in the neutrino story was Enrico Fermi,* the great Italian—American physicist who died in 1954. We are indebted to him for, among other things, the name "neutrino". In his original paper Pauli called the neutrino the neutron. By the time Fermi came to work on *his* paper the real neutron had been discovered, and he had to look for a new name. In Italian neutron is "neutrone", which, literally translated, means something like "large neutral one". As sort of a joke, a colleague of Fermi's suggested that the Pauli particle might be called "neutrino" or "little neutral one", since, it was already clear that it would have to be nearly electrically neutral.

More importantly it was Fermi who formed the first quantitative neutrino theory. This theory involves advanced and abstract notions of quantum mechanics and we will only give the general flavor of his ideas

*Fermi received the Nobel Prize in 1938 for identification of new radioactive elements and discovery of nuclear reactions affected by slow neutrons. See *The First Reactor*, another booklet in this series, for an account of how he led the team that built the first nuclear reactor.

and his principal conclusion. This was to derive a formula for the distribution of electron energies in beta decay; this is called the electron energy spectrum.

Fermi exploited the notion that elementary particles are constantly transforming themselves into other elementary particles. If such a transformation satisfies the conservation of energy, then it will display itself as a real decay process in which the sum of the rest energies of the emitted particles is less than the rest energy of the original particle. Once it has been transformed a particle cannot put itself together again. By using quantum mechanics he computed the probability of such a beta transformation in the case of an unstable nucleus and how the electron energies are distributed. He found this curve for the energy distribution:



In this figure we have drawn the energy distribution of the electrons—a quantity that we called N(E)—as a function of the electron energy E. You can think of N(E) as follows: Where N(E) is zero *no* electrons can be emitted. This reflects the conservation of energy and momentum. N(E) is zero below a certain minimum electron energy and then it rises to a maximum, which occurs at the energy where electrons are most likely to be emitted. It then falls off sharply to zero indicating that it is hard to emit the most energetic electrons in beta decay even though the conservation of energy and momentum allows them to be emitted. Above a certain maximum energy, N(E) is again zero and this reflects the fact that electrons with an energy greater than this maximum cannot be emitted without violating energy and momentum conservation. In deriving this curve Fermi has gone far beyond the simple requirements of the conservation of energy and momentum and he has made use of the full quantum theory along with the neutrino hypothesis.

Curves like this are a consequence of assuming the existence of an invisible particle (the neutrino) and of following the usual rules of quantum mechanics. The Fermi theory of beta decay gives excellent agreement with many experiments.*

*Disagreements can be explained by refining the theory—a process that is still continuing.

Enrico Fermi

There are two additional points about the Fermi theory that should be mentioned. By measuring the maximum electron energy emitted in a beta decay, we also know the mass of the neutrino if we know the masses of the other particles involved—the electron, the parent, and daughter nuclei. This is a consequence of the energy and momentum conservation equations, which we can easily rewrite with a non-zero, unknown, neutrino mass. Measuring these masses and energies is not as easy as it might appear and for this reason the mass of the neutrino is imperfectly known. The most recent result gives

$$m_{\nu} < 200 \text{ eV}$$

which means that experiment excludes masses any larger than 200 eV but the mass may very well be smaller or even zero.* The simplest and most elegant theory of the neutrino is given by assuming that it has exactly zero mass, and this is the assumption that is universally made by physicists.

The second point depends on the details of the Fermi theory. The function N(E) determines the relative probability for emitting electrons of a certain energy. Where N(E) is small, for example, it is unlikely that an electron of that energy will be emitted in beta decay. If we compute the area under the curve for N(E)† this gives a measure of the probability that the decay will take place because we are considering the relative probabilities that the decay can occur with various energies.

If we know, out of a sample of radioactive beta-decaying nuclei, how probable it is for a nucleus to decay in 1 second, then we also know about how long particles in the sample will live. Knowing N(E) enables us to say a great deal about the lifetimes of beta-decaying nuclei. Fermi's N(E) predicts that the probability per second for beta decay is approximately proportional to the fifth power of the difference between the masses of the parent and daughter nuclei. Among the beta radioactive nuclei there is a wide variation—approximately a factor of ten—in this mass difference.

For example, the neutron beta decays into a proton, electron, and neutrino and here the neutron–proton mass difference is 1.3 MeV. The neutron lifetime is about 1000 seconds. In this decay the maximum kinetic energy an electron can have is 0.782 MeV. However, tritium, an

*Note that the electron's rest energy is about 0.51 MeV so that the maximum neutrino mass allowed by experiment is less than a thousandth of the electron mass.

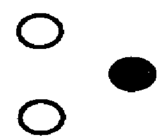
†A process that is called the integration of N(E).

isotope of hydrogen with 1 proton and 2 neutrons in its nucleus, beta decays into helium-3, an isotope of helium with 2 protons and 1 neutron in *its* nucleus. Because of the small mass difference between these two nuclei, the electron can carry away only 0.02 MeV of kinetic energy, at most; and tritium lives for 12.4 years! This is an excellent example of how the Fermi theory predicts wide ranges in the lifetimes of the beta unstable nuclei because of the varying amounts of energy that can be released in the different decays. The theory and its successes are a brilliant confirmation of the neutrino hypothesis that underlies it.

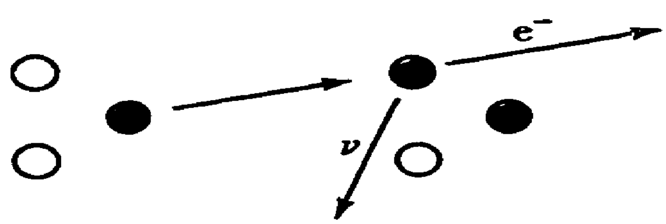
The Fermi theory dealt with *electron* beta decay, that is, with decays in which an electron is emitted. In order to balance the charge this must mean that one of the neutrons in the nucleus has converted itself into a proton. The prototype of this reaction is the neutron beta decay itself

$$n \rightarrow p + e^- + \nu$$

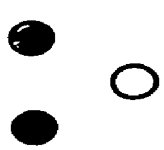
A heavy nucleus beta decay is the transformation of one of the neutrons bound in the nucleus into a proton, which remains in the nucleus, and an electron and a neutrino, which escape. The nucleus increases its charge by one unit, i.e., it becomes the nucleus of a chemically different substance.



Tritium with 2 neutrons, represented by open circles, and one proton represented by the dark circle decays.



into the nucleus



which is He_3 a stable isotope of helium. In other words one of the neutrons ○ converts itself into a proton ●, an electron e^-, and a neutrino ν.

(In the example on page 31 hydrogen was transformed into helium.)

We might be tempted to ask if in some decays a proton can be transformed. Of course, a free proton is lighter than a free neutron and so it can never decay into a neutron. This fact is reflected in the observed stability of the proton; it lives longer than 10^{27} years. However a proton bound in a nucleus is a different matter. All that is relevant here is that the nucleus, which is left over after the proton decays, be lighter than the original parent nucleus. If we write the decay symbolically as

$$p \rightarrow n + \nu + X$$

it is clear that this X must have a positive charge whereas the electron has a negative charge. Into what can this bound proton decay? In order to make this decay work we need a positive electron.

Particle—Antiparticle

Fermi did his work in 1933, and the year before the American physicist Carl Anderson discovered the positive electron—now known as the positron—that would be needed for the beta decay of protons bound in nuclei. (Physicists call both electron and positron decays "beta decays".) This positive electron is a mirror image of the negative electron. It has the same mass, the same spin, but the opposite charge of the negative electron. The electron and positron form a *particle–antiparticle* pair. If an electron and positron come together they can annihilate each other, and out of this annihilation two photons emerge.

$$e^+ + e^- \rightarrow \gamma + \gamma$$

The discovery of the positron had been anticipated by theory. In this case it was the English physicist Paul A. M. Dirac* who, in the late 1920s, had predicted its existence. Dirac formed a theory of the electron that united relativity and quantum mechanics and contained the positron as an unavoidable consequence. Since the rest of the theory was in such excellent agreement with experiment, Dirac took the position that the positron *had* to exist.

When Fermi began working on the neutrino theory it was inevitable that he apply Dirac's ideas to the neutrino. He was led to the idea that if Pauli's neutrino existed then Pauli's antineutrino must also exist.

*Dirac received the Nobel Prize in 1933 for the discovery of new forms of the atomic theory.

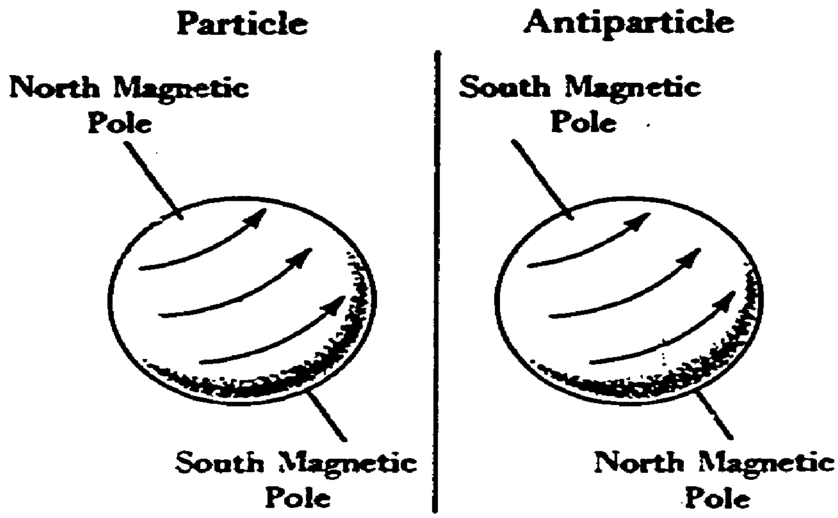
P. A. M. Dirac

Since neither particle had been directly observed, and were not observed until 1953, physicists in the 1930s and 1940s had a queasy feeling about the whole business. This feeling was compounded when many theorists began asking themselves: What is the physical distinction between a neutrino and an antineutrino? For charged particles one of the distinctions between a particle and an antiparticle is very simple. If the particle has a positive charge then the antiparticle must have a negative charge.* However, if a particle is electrically neutral how does it differ from its antiparticle?

We can begin by considering the case of the neutron and the antineutron, which was also observed in 1955. Both have the same spin, mass, and the same strong interactions with matter and antimatter respectively. The neutron beta decays with a lifetime of about 1000 seconds and the antineutron beta decays into a positron, antiproton, and some sort of neutrino (a neutrino or an antineutrino), also (although this has not yet been measured) with the same lifetime. Both are electrically neutral. However, it is a well-known experimental fact that the neutron is constantly transforming itself virtually through the strong interactions into electrically charged particles and thereby acquires an electromagnetic structure. For the purposes of discussion physicists often divide this structure into two parts—an electric part and a magnetic part. The electric part is similar to the electric structure of atoms. An atom has a large number of electrons wandering around in it and this gives it an electric shape and size, which can be measured by probing the atom with charged particles or photons.

The neutron also has a shape and size, but this is due to particles like the charged pi-mesons that play an important role in its structure. However, both atoms and the neutron have a magnetic structure as well. If the neutron is placed in a magnetic field it will behave as a tiny magnet. This magnet can in principle point in only one of two directions once the direction of the neutron spin is fixed. (One can argue that a magnet has to point in some direction and that the only direction that can be associated with a neutron is the direction of its spin.) Experiments show that the neutron's magnet always points anti-parallel to the spin. If the spin is pointing in the plus z direction

*Which is called the particle or the antiparticle is really irrelevant, but physicists tend to call the most familiar species, the particle. Thus, the electron, which was known long before the positron, is called the particle while the positron is called the antiparticle. Similarly, we call the positively charged proton the particle and the negatively charged mirror image of the proton discovered in 1955 the antiproton.



Particle and antiparticle magnetic poles.

the magnet points in the minus z direction. (For the proton, the magnet points in the direction of the spin.)

The theory of particles and antiparticles then predicts that the magnet associated with the antineutron should point opposite to the magnet associated with the neutron, i.e., in the direction of the spin. Here is a distinction that we can get our teeth into. The only trouble is that, if our present theoretical ideas are correct, the neutrino does not have a magnetic interaction!

The arguments that lead to this conclusion are very subtle and we cannot give the details here. We *can* say that this fact depends on the assumption that the neutrino has no mass. The critical point is the one mentioned at the end of the previous section—the spin of the neutrino always points anti-parallel to its momentum. This depends on its having zero mass and hence moving with the speed of light. (If it had a mass and moved slower than the speed of light we could imagine running beside it so that the direction of its momentum appeared to change but not its spin. Hence the correlation between neutrino spin and momentum would be dependent on the coordinate system in which it was observed. It is only in the special case of zero mass, or speed of light, that this correlation is independent of any reference frame.)

If the neutrino had a magnet associated with it we could imagine an experiment in which we put the neutrino in a magnetic field and then used this field to change the spin of the neutrino but not its momentum. A magnetic field could hook onto the neutrino's spin magnet and flip it so that it was lined up with the momentum. But this is impossible since *all* neutrinos have their spins opposed to their momenta; thus a magnetic neutrino coupling would allow us to transform the neutrino into a nonexistent particle. This abstruse line of argument does suggest

the physical distinction that might exist between a neutrino and an antineutrino. If the spin of the neutrino points in the opposite direction to its momentum then the spin of the antineutrino points *in* the direction of the neutrino's momentum.

This also fits very nicely with the theoretical picture.

The Conservation of Leptons

In view of this distinction between the neutrino and the antineutrino we can say that if the neutrino had a magnetic interaction we could use a magnetic field to transform it into an antineutrino; this transformation is one that physicists believe to be strictly forbidden. This belief is so firmly held that it has been elevated to a principle with the imposing name—*The Conservation of Leptons.* Lepton means light (as opposed to heavy) in Greek, and leptons are lighter than any other elementary particle such as a proton. (Protons and neutrons belong to a class of heavy particles that physicists call baryons.)

There are four known leptons and four known antileptons, but we will stick to the electronic leptons—the electron and the neutrino of beta decay—and in the next part of this booklet we will discuss the other two. To each of these leptons we assign the number 1, while to each of the antileptons we assign the number −1. Thus we can summarize these assignments in a little table

Name of Particle	Symbol	Lepton Number
Electron	e^-	1
Positron	e^+	−1
Neutrino	ν	1
Antineutrino	$\bar{\nu}$	−1

The conservation of leptons can now be simply stated in terms of these numbers. Take all the leptons and antileptons that enter into a given reaction and add their lepton numbers algebraically, that is, keeping track of the signs and subtracting whenever an antilepton appears. Do the same thing for the leptons that emerge from the reaction. Assign zero lepton number to any particle (like the neutron) that is not a lepton. If the sums of the initial and final lepton numbers agree with each other then the reaction can occur. If they disagree the reaction is forbidden. That is the principle of lepton conservation.

To take a simple but characteristic example, let's consider the beta decay of the neutron. In this decay the entering particle is a neutron with zero lepton number while the emerging particles are a proton with zero lepton number and an electron with number 1. Hence we are forced to have an antineutrino with number −1 to make the addition work. Thus the reaction should be written

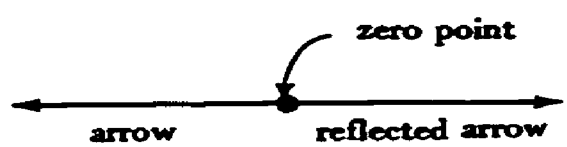
$$n \rightarrow p + e^- + \bar{\nu}$$

The principle enables us to draw, with the rest of the information given above, the very non-trivial conclusion that the antineutrino emerging with the electron and proton must have its spin parallel to its momentum.

The Fall of Parity

All this is a very long way from Pauli's 1931 invention. In fact, none of these properties of the neutrino were imagined before 1956.* The big event of that year was the discovery that the conservation of "parity" broke down in the weak interactions like those responsible for the beta decay of the neutron.

Parity is another of those rather difficult abstract ideas, which a popular exposition like this one can only hint at the flavor of. Parity conservation or parity symmetry refers to the equivalence of physical events using right and left-handed coordinate systems. Below I have drawn a right and a left-handed system. I have deliberately oriented the left-handed system to illustrate the fact that right-handed and left-handed systems are related to each other by "reflecting" all the axes. The figure below illustrates the distinction between a reflection and a rotation. In the first picture we have "reflected" the arrow about the zero point.



In the second picture we have "rotated" the arrow by ninety degrees.

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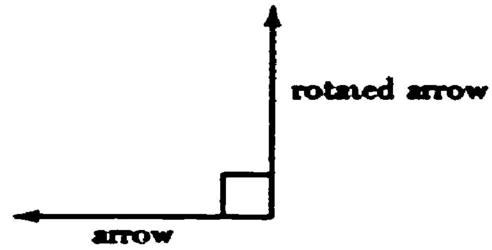
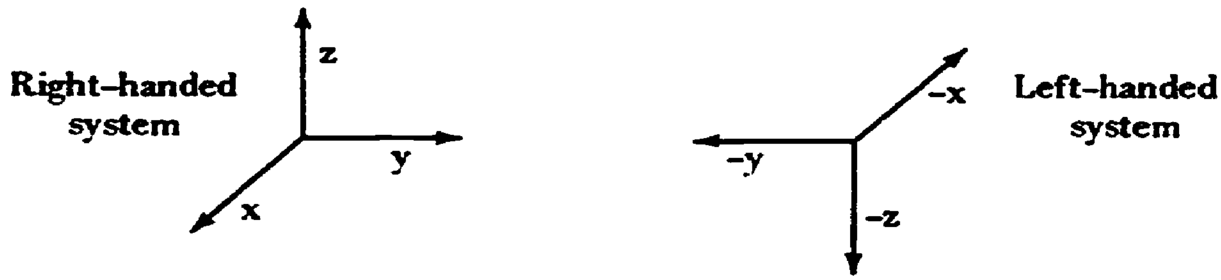
*In the late 1920s the mathematician Herman Weyl wrote down a neutrino theory that is essentially identical to the modern one. However, most physicists were unaware of his work, and it was not until 1956 that it was rediscovered and found to be relevant to the actual neutrino.



In this case if we continue the rotation by another ninety degrees we produce a configuration that is identical to the reflection. This is possible in two dimensions. But in three dimensions it is not. Thus the configurations



are related by reflection of the arrows but cannot be related by any rotation or combination of rotations. No rigid rotation will transform one system into the other. (Try it with the thumb and two fingers on the right hand and see if you can rotate them so that they look like the reflected configuration made out of the same fingers of the left hand. You cannot and it isn't worth spraining a wrist trying to do it.) A reflection is necessary to make the transformation and so parity symmetry or invariance is sometimes called "reflection" invariance.

If a pre-1956 physicist had been asked if using one system or the other made the slightest difference to physics he would have said, "Certainly not". A physicist's intuitive experience, gained by many years of experimentation in classical physics, would have led him to believe that no experiment would be sensitive to whether or not he chose to describe it with a right-handed or a left-handed system. Laws like those in Newton's classical mechanics do not change under transformations from right-handed to left-handed systems. Some textbooks in classical mechanics use right-handed systems and some use left-handed systems and you can learn mechanics from either sort of book with no trouble. By just reflecting axes one can transform the descriptions in one book to those in the other.

It is just this equivalence of description that is meant when a theory is called "parity symmetric" or "reflection invariant". It became natural to think that parity symmetry was a sort of universal principle like the conservation of energy and momentum. We are indebted to the

two Chinese–American physicists, Tsung Dao Lee and Chen Ning Yang,* for wondering if this principle could be extended to the weak interactions, for suggesting the tests that needed to be made and, above all, for indicating that this extension had never been tested experimentally.

During the summer of 1956 several groups of physicists began experiments to test parity conservation and by January 1957 it was absolutely certain that the weak interactions were not parity symmetric. The Weyl theory of the neutrino was subsequently resurrected. (Several physicists, including Lee and Yang, rediscovered the theory independently.) This theory predicted that the neutrino's spin was correlated with its momentum. The Weyl theory was never taken seriously before 1956 just because such a correlation violated parity symmetry. This is again a subtle matter. The point is that angular momentum, or spin, is not what physicists call a true vector. Below is a table of the way in which certain physical quantities transform when one goes from a right- to a left-handed description.

Type of object	Example	Transformation
Vector	Momentum	Into its negative
Pseudo-vector	Spin	Unchanged
Scalar	Energy	Unchanged
Pseudo-scalar	Helicity	Into its negative

To be parity symmetric a theory cannot contain pseudo-scalar quantities like helicity—the correlation between spin and momentum—since these change sign when one switches from a right- to a left-handed system. In beta decays, for example, the electron's momentum is correlated to the spin of the nucleus that is emitting it. It was the observation of such correlations which led to the conclusion that parity symmetry breaks down for such decays.

The orbital angular momentum L is defined as the "vector product" of two true vectors—the position vector r and the momentum vector p; thus $L = r \times p$. If one makes a reflection of all the axes, thus changing from the right- to left-handed system, a true vector changes sign. Since L is the product of two true vectors these sign changes cancel out and hence L is not a true vector. Neither is the spin. However, the momentum p is a true vector. To say that the neutrino spin is correlated to its momentum is to say that there is a correlation between

*Lee and Yang received the Nobel Prize in 1957 for suggesting the experiments that led to the downfall of the conservation of parity principle.

C. N. Yang

Tsung-Dao Lee

a true vector and a "pseudo" vector. Such correlations are forbidden if the theory is parity symmetric. After it was discovered that the weak interactions were not parity symmetric the possibility of such correlations was reopened and it became a matter for experiment to decide if they existed.

After the long and rather abstruse considerations in this chapter we turn next to the more concrete question of how the neutrino was actually observed and how experiments were designed to measure the correlation between the neutrino spin and its momentum. In the next chapter, we have a little surprise for the reader. The title perhaps gives it away.

THERE ARE FOUR OF THEM!

In the last section we saw how Pauli was led to the invention of the neutrino to save the conservation of momentum and energy. To this list we can also add the conservation of angular momentum. This is very clear in the primordial beta decay

$$n \rightarrow p + e^- + \bar{\nu}$$

All the particles in this decay, n, p, and e^- have spin $\frac{1}{2}$. If it were a two-body decay it wouldn't be possible to make the angular momenta come out right. There isn't any way of adding up the angular momenta of two spin-$\frac{1}{2}$ particles to yield an angular momentum of $\frac{1}{2}$. This figure illustrates the addition of spin angular momenta. We first add two spins, and there are two basic results.

$$\uparrow\uparrow \quad \text{or} \quad \uparrow\downarrow$$

The first corresponds to a total spin of 1 while the second picture represents a spin zero since the spins subtract. In neither case do we get a spin of $\frac{1}{2}$. With three spins we can have, for example, a configuration like

$$\uparrow \ \downarrow \ \uparrow$$

which would give a spin of $\frac{1}{2}$.

The assumption that the neutrino spin is $\frac{1}{2}$ is the basis for the discussion of the neutrino helicity in the last two sections—the correlation between the neutrino spin and its momentum. A helix is a curve that winds around like the coils of a screw. When physicists first started thinking of the correlation of the neutrino's spin with its momentum they imagined the particle buzzing along and turning about the momentum axis like a spiral. The neutrino has negative helicity since its spin is opposed to its momentum, while the antineutrino has positive helicity because its spin is correlated to the direction of its momentum.

By the end of the Second World War a great deal was known indirectly about the neutrino. It had spin $\frac{1}{2}$ judging from angular momentum conservation, and it had little or no mass according to the measurements of the electron spectrum in beta decay. It also had no observable charge. There were two arguments for this. It left no tracks in particle detectors as it would have done if it had had a substantial

charge.* Secondly electric charge is one of those quantities in physics that appears to be absolutely conserved; it is never gained nor lost in any reaction.

The neutron charge is zero within the limits of experimental accuracy. Hence the combined charges of proton, electron, and antineutrino must add up to zero if charge is to be conserved. But the charge on the proton and electron are equal and opposite. Thus the neutrino charge must be essentially zero. The present experimental limit on this is that the neutrino's charge is at most 10^{-19} e where e is the charge of the electron. Since it leaves no tracks in particle detectors its magnetic interaction is very small or zero; this fits very nicely with the theoretical ideas discussed in the last chapter. All this was known by 1950. The one thing that was not known was whether or not the neutrino actually existed in the sense that it could be directly observed.

Neutrino Catching

The experiments designed to observe the neutrino (or antineutrino) involved schemes for absorbing it in a target. Since the neutrino interactions are so weak the experimenter must contend with four general problems:

1. The strongest possible source of neutrinos or antineutrinos should be found.

2. The target should be as large as possible since the more nuclei there are the greater the chance that the neutrino will interact with one.

3. The whole target area must be shielded against the constant background of cosmic radiation† and, perhaps, radiation from whatever source is producing the neutrinos in the first place. If this isn't done then the very rare neutrino event can easily become confused with interactions of other background particles with the target.

4. An observation process must be chosen that is so characteristic of neutrino absorption that it cannot be confused with anything else.

Cowan–Reines Experiments

The physicists Clyde L. Cowan, Jr. and Frederick Reines, of the Los Alamos Scientific Laboratory in New Mexico, carried out the first successful neutrino experiment, which had all these properties. We can go through these to understand how and why the experiment was designed.

*When a charged particle passes through the detector's material it interacts with the charged particles in the material and this interaction is what is detected.

†Cosmic rays are charged particles like protons or mesons coming to earth from outer space. See *Space Radiation*, a companion booklet in this series.

1. The strongest source of neutrinos on earth are fission reactors. With the development of very large fission reactors during and following World War II, intense and sustained sources of neutrinos (or, strictly, "antineutrinos") became available for new attempts to detect this particle. Without going into the details of reactor design, we can say that, as the name implies, a reactor operates by a chain reaction. A neutron causes a heavy element like uranium to split, or fission, and neutrons emerge, along with some heavy radioactive nuclear fragments. If several neutrons emerge for a single neutron digested, then these can fission other uranium nuclei and the process multiplies.

For our purposes the key idea is that such a reactor is an enormous tank of fission fragments. These objects beta decay and antineutrinos emerge. The experiment is thus designed to detect antineutrinos, and this is what was found in 1953.

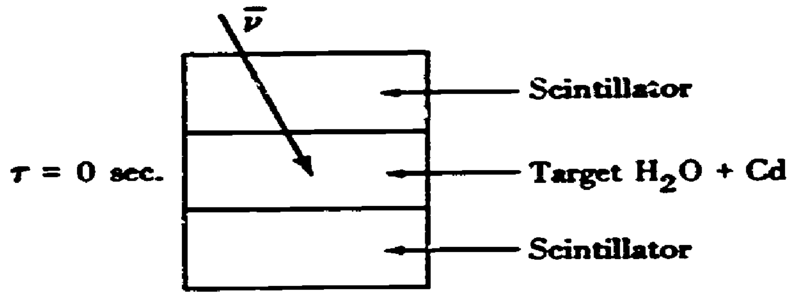
As we shall see under 4 below, this helps enormously in the design of the experiment, since (by lepton conservation) if we begin with an antineutrino with lepton number −1 we must end with something with a lepton number −1—either another antineutrino (which doesn't help since it is no easier to detect than the one we started with) or a positron, which is a very nice particle to work with. Thus the "good" absorption reaction will have the general form*

$$\bar{\nu} + p \rightarrow n + e^{+}$$

At this point you may object. Up to now we have discussed only decay processes in which neutrinos are emitted. Why should we assume that the same ideas apply to absorption processes? Here again we can take advantage of the Fermi theory. If the Fermi theory makes correct predictions for the decays then it also makes correct predictions for these absorption processes. All that is involved is a little shuffling of the mathematical entities of the theory in order to deduce what these predictions are.

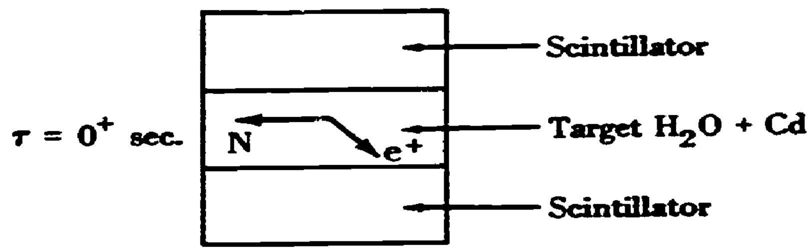
Thus Cowan and Reines were led to set up their apparatus at one of the largest nuclear reactors available. For their first attempt, this was a newly built one at the Hanford Engineering Works of the AEC. Placing their equipment very close to this pile, they found that, while their design was apparently quite good for use near a reactor, their equipment did not discriminate well enough against cosmic rays. Their second and more successful try was then with a newer and larger

*We give it for the proton but it works just as well for a heavy nucleus with lots of protons.



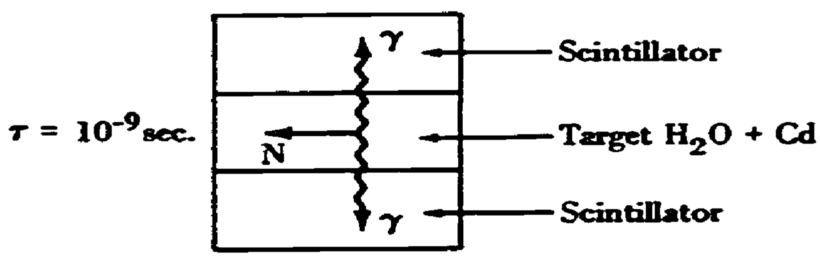
$\bar{\nu}$ enters target.

①



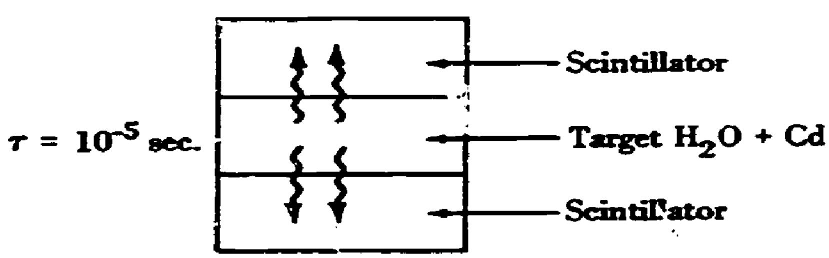
Positron and neutron created in $\bar{\nu} + p \to N + e^+$.

②



Two γ's enter the scintillators after 10^{-9} second.

③



γ rays enter the scintillators after the neutron has been captured by the cadmium. ④

Sequence showing the time evolution of the Cowan-Reines experiment.

detector placed near a newer and larger reactor at the AEC's Savannah River Plant in South Carolina. The antineutrino flux emerging from this reactor is in the vicinity of 5×10^{13} per square centimeter per second.

2. The target size is limited by practical considerations. One wants to pack a lot of material into a small volume so that the number of target protons will be as large as possible. This limits targets to liquids or solids and in these experiments the targets were two metal tanks about 3 inches high and 6¼ by 4¼ feet wide. These contained nearly 200 liters of a water—cadmium acetate solution whose protons provided the targets for the antineutrino absorption.

3. In this experiment (and this is typical of most experiments done in elementary particle physics) the shielding was of two varieties. A lead shield that varied in thickness from 3 to 8 inches was placed around the target area. Then, just in case some cosmic ray managed to get through the lead, the target was placed below a detector that would indicate if such a charged particle had gotten through. If a neutrino event occurred coincidentally with the passage of a cosmic ray, that event was eliminated as a candidate for a real neutrino absorption process.

Finally, of course, one can shut down the reactor so that no neutrinos are emitted, and then see if the apparatus still detects "neutrino" events. These would be fake and might be caused by inevitable bits of cosmic-ray background that leaked through the anticoincidence apparatus, or by some fluke in the electronics of the machinery. When the reactor is turned on again there should be a net increase in real neutrino events and this net increase above the background is what they were looking for.

4. The real ingenuity of the experimenters shows itself in selecting the right "signal" to observe. Cowan and Reines took advantage of the fact that antineutrinos produce positrons, which annihilate themselves with electrons in the reaction

$$e^+ + e^- \rightarrow \gamma + \gamma$$

that produces two gamma rays, i.e., very energetic photons. (The water atoms in the target are loaded with electrons.)

This annihilation takes place most readily once the positron has been slowed to rest by collisions with the atoms. From the conservation of energy and momentum we know that the two photons that come out must have equal and opposite momenta and exactly the same energy. Their total energy is the sum of the rest energies of the electron and positron. Since both have the mass of the electron, each photon has an energy that is identical to the rest energy of an electron—0.51 MeV.

$$\xleftarrow[0.51\ \text{MeV}]{\gamma} \quad \xrightarrow[0.51\ \text{MeV}]{\gamma}$$

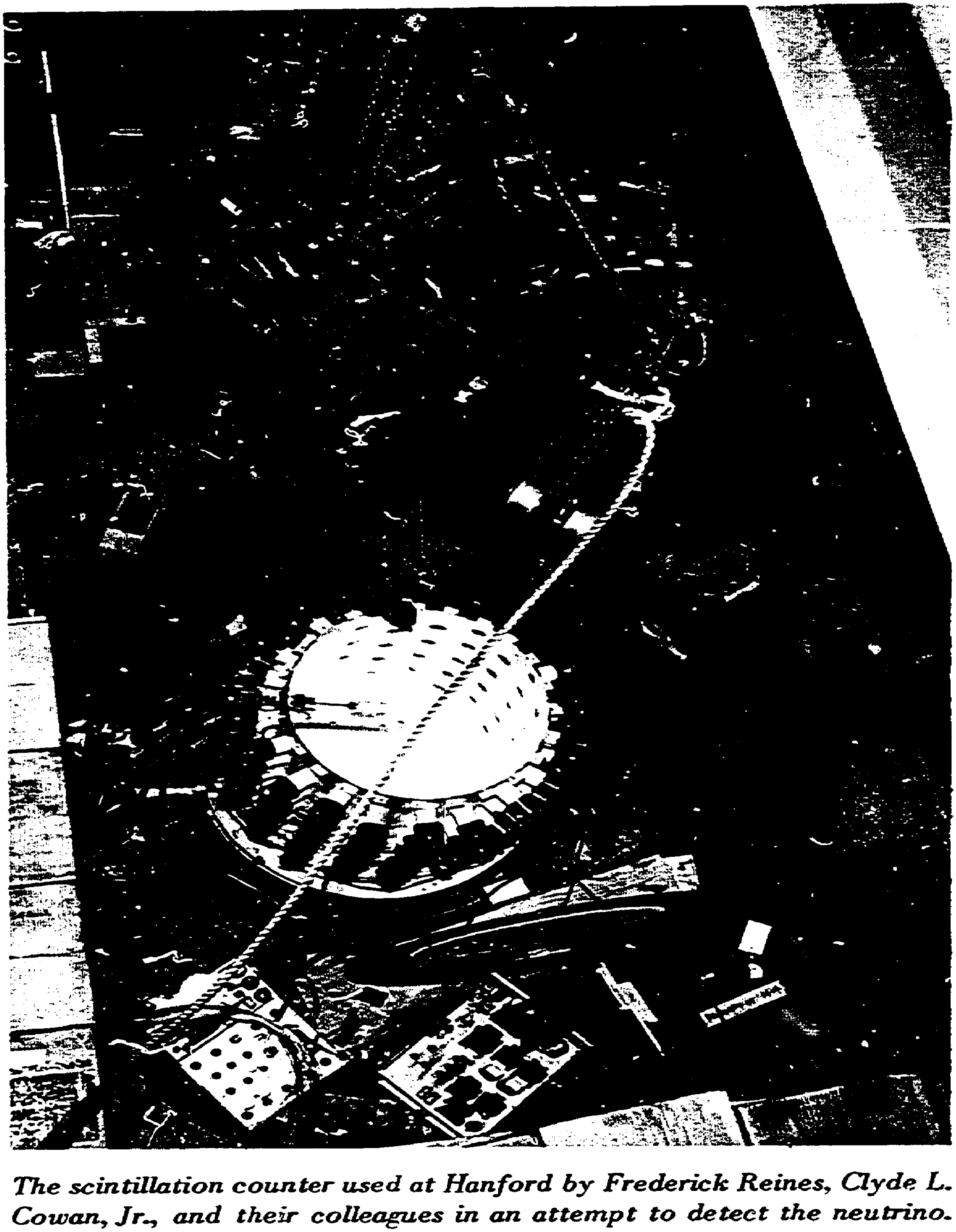
The trick is to verify that such an annihilation has taken place. To this end a photon detector is placed above and below the target. Cowan and Reines used two large vats of liquid that gave off light scintillations when a photon impinged on it, and this light was observed by photomultiplier tubes. According to the conservation laws if one photon from the annihilation travels up to one scintillator the other one must travel down to the other scintillator. So the experiment is arranged to detect only those events in which there are two simultaneous scintillations.

With all these precautions, stray positrons can still get into the target from background radiation and the scintillators may flash accidentally because two photons happen to pass through them at about the same time. To eliminate these accidental events the cadmium in the target comes into play. Cadmium is a neutron absorber, and a cadmium nucleus, which captures a neutron, is transformed into a different isotope. In the process several gamma rays are emitted that carry off any excess energy.

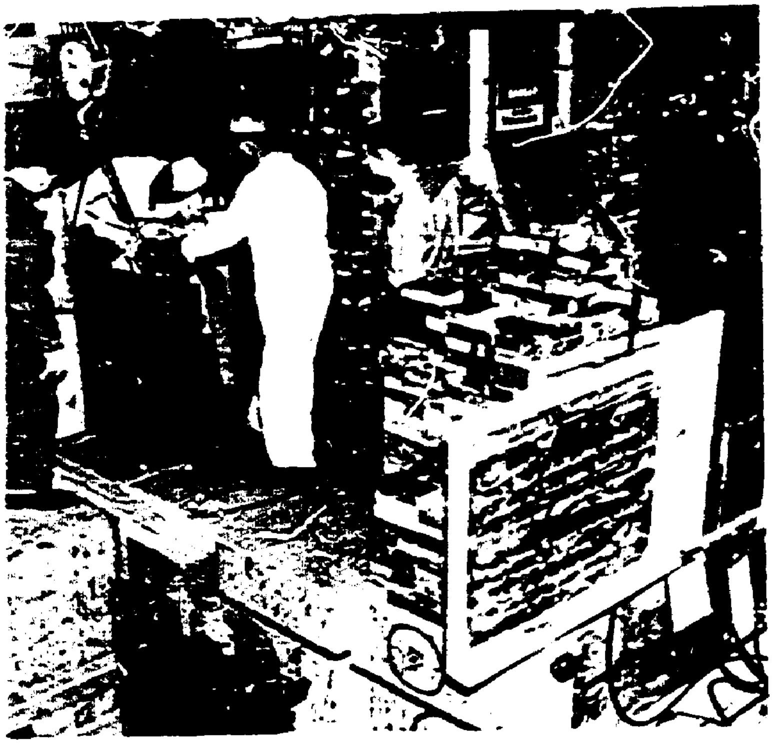
Now we can see the whole plot. An antineutrino enters the target and converts a proton into a neutron with the release of a positron. About 10^{-9} second later, the positron finds an electron that it annihilates. Then two photons enter the scintillators, which flash and are "read" by the photomultiplier tubes. Meanwhile the neutron has been (after its creation in the neutrino absorption) wandering around in the water–cadmium solution looking for a cadmium nucleus. In about 10^{-5} second it finds one. There is a "long" interval between the positron flash and a second flash caused by the captured gamma rays arriving at the scintillator. This time lapse is very clearly separated by fast light detectors and the whole sequence of events is spelled out clearly. This sequence is the signal that Cowan and Reines looked for.

This experiment was conducted during several months in 1955–1956. It took months because they measured a maximum antineutrino signal rate of 2.88 ± 0.22 antineutrino signals *per hour*, and there were only three captures an *hour*! This confirms everything that one suspected about the weakness of the neutrino, or antineutrino, force. The fact that the antineutrino absorption was observed at all is a tribute to the experimental skill of Cowan and Reines* to say nothing of the genius of Pauli, who recognized that such a particle had to exist.

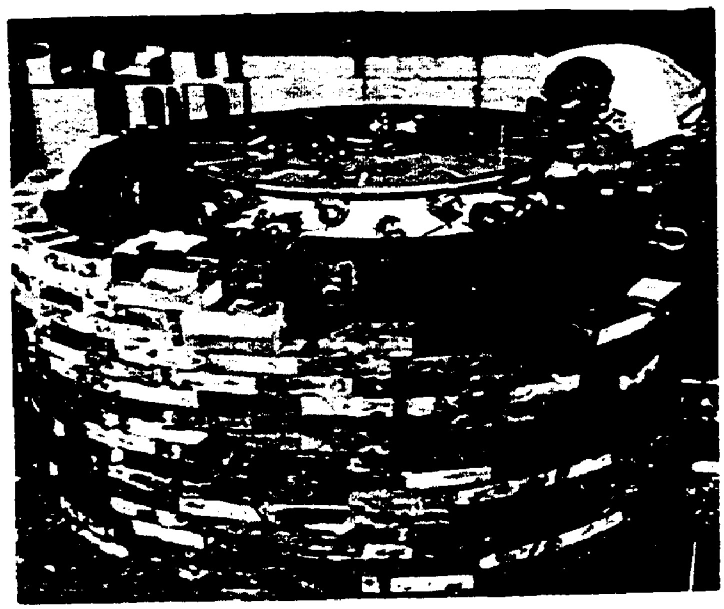
*According to a story that made the rounds after the antineutrino was observed, Cowan and Reines gave a dinner at Los Alamos in which each guest received a small, carefully wrapped "empty" box. A card inside said, "This box is guaranteed to contain at least 100 neutrinos."



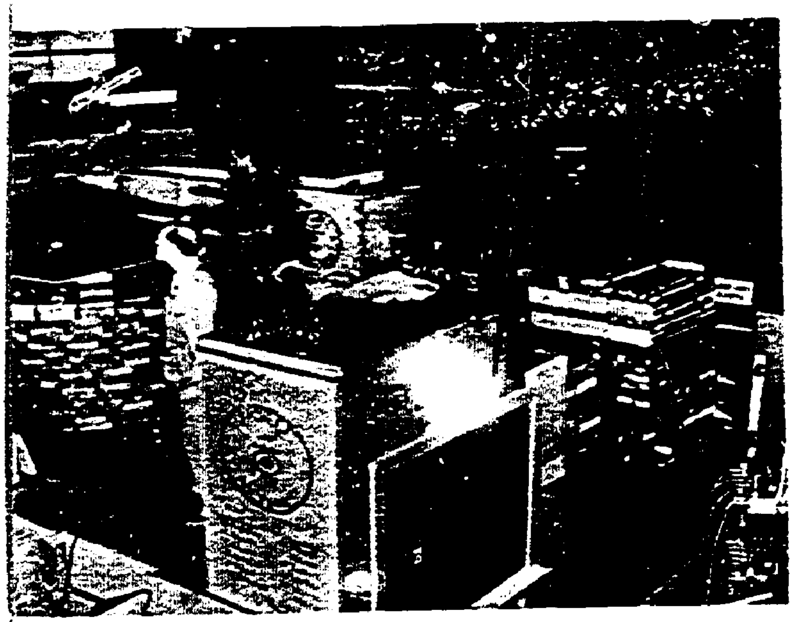
The scintillation counter used at Hanford by Frederick Reines, Clyde L. Cowan, Jr., and their colleagues in an attempt to detect the neutrino. The counter is the cylindrical object at the bottom. (See pages 50 and 51 for other pictures of this experiment.)



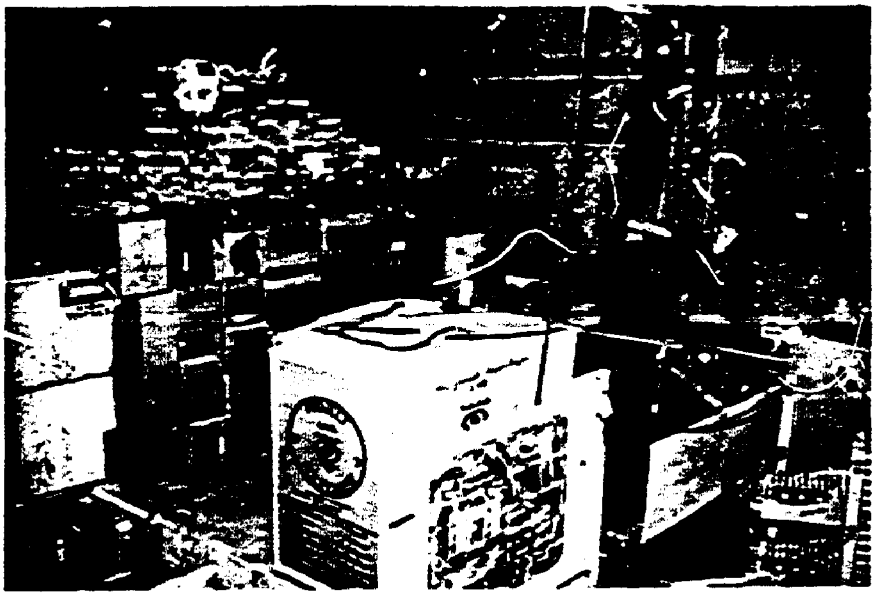
R. Schuch and F. Harrison supervise placement of lead shield around the detector.



The detector is adjusted inside its kiva. (Kiva is a Navajo word for a building without windows that sits inside another building.)



Large trays of Geiger counters are placed over the detector to shield it from cosmic rays.



A pyramid of lead bricks on top of blocks of paraffin can be seen in this view of the completed shield. (The research program was called Project Poltergeist because a poltergeist is an invisible, mischievous, and very illusive ghost.)

Reines takes notes while Cowan reads dial settings.

Some of the researchers: left to right, Lt. P. Powell, USN, Dr. F. N. Hayes, Mr. K. Perkins, Dr. F. Reines, Dr. E. C. Anderson, and Dr. C. L. Cowan.

Conservation of Lepton Number in Neutrino Reactions

About the time of the Cowan–Reines experiment, Raymond Davis, Jr., of Brookhaven National Laboratory in Upton, Long Island, New York, began a second reactor experiment designed to test the conservation of lepton number in neutrino reactions. Davis wanted to verify that antineutrinos from the reactor create positrons but not electrons (which would be forbidden by lepton number conservation). To test this he proposed to set an experimental limit on the forbidden reaction*

$$\bar{\nu} + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

If lepton number conservation is good then this reaction should not be seen at all. If it is completely violated then this reaction should be about as frequent as in the Cowan–Reines reaction.

Chlorine is a good target choice since it can be stored in large quantities in such liquids as carbon tetrachloride, a commonly used cleaning fluid. Davis's target was a vat containing 1000 gallons of cleaning fluid. If the forbidden reaction were to take place the final nucleus produced would be a radioactive isotope of ^{37}Ar. Davis flushed out the cleaning fluid tank from time to time with pure helium gas, which pushes out any argon nuclei as well. The helium was then examined for radioactive argon.

In this way he showed that the forbidden reactions can occur at most at a rate of about a thousandth of the Cowan–Reines reaction. If there had been a single clear-cut case in which lepton number conservation was violated, the law would have to be modified or thrown out. This doesn't confirm the law absolutely, but it tells us that if there is a violation it must be a small one.

Hideki Yukawa and the Strong Interactions

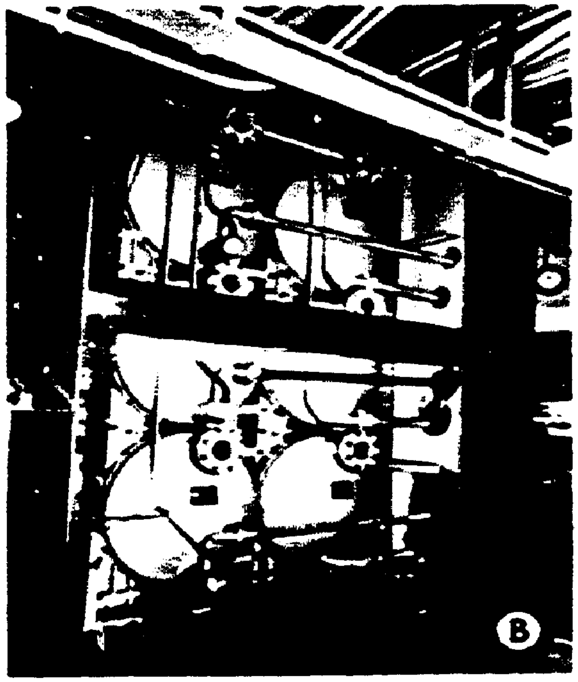
We are now ready to discuss the surprise promised in the last chapter. Before revealing it we must digress a little to explain some of the events that lead up to it.

To begin with there was the discovery of the mesons, which can be traced to the inspired guess of a Japanese theoretical physicist, Hideki Yukawa.† In 1935 Yukawa proposed a theory of strong interactions.‡

*Cl stands for chlorine and Ar stands for argon.

†Yukawa received the Nobel Prize in 1949 for his prediction, 14 years before the discovery of the pi-meson.

‡The interactions that hold neutrons and protons together in the nucleus.

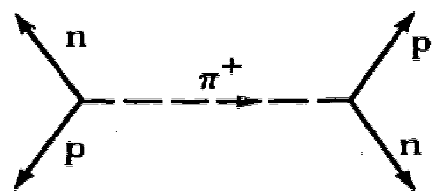


(A) The neutrino detector set up at Brookhaven for testing. This is a stack of six 500-gallon tanks of carbon tetrachloride, which is circulated between pairs of tanks by a pump. On the side are three sets of pumps and valves supported by a heavy iron frame. (B) The tanks, located in an iron vessel that was used for water shielding, in place at Savannah River. The door of the water tank is removed. (C) Here the water tank door is closed. Dr. Don S. Harmer of the Georgia Institute of Technology operates the system for collecting ^{37}Ar, which was a series of condensation traps and charcoal traps that removed argon from the helium gas. The helium was bubbled through the tanks in series to remove ^{37}Ar produced in the tanks. In these experiments, Mr. Davis and his colleagues did not observe ^{37}Ar produced by the antineutrinos from the reactor, thus demonstrating that neutrinos and antineutrinos are not identical particles. According to present views these particles have their spins oriented in opposite directions.

He said that *Action at a Distance* was nonsense. If these particles influence each other there must be something that they transmit between them, such as a quantum or a particle, just as two electrons transmit light quanta to induce their mutual interaction.

What is of special significance here, and this Yukawa understood very clearly, is that the nuclear force has a short range. The ordinary Coulombic electric force between two electrons has a very long range. It falls off at large electronic separations with the same inverse-square law as the force of gravity and we know that the force of gravity extends, for example, all the way from the earth to the moon and beyond. The nuclear force is so short-range that in solid matter one nucleus hardly affects its neighbors and most of the properties of matter can be understood in terms of the electric forces acting among the atoms. The range of the nuclear force is about 10^{-13} centimeter.

Now in Yukawa's model the nuclear force arises when two nucleons, a neutron or a proton, exchange a lighter particle that we now call a meson with a mass 200 times that of an electron or one-ninth that of a proton. Below is the exchange of a charged pi meson by two nucleons.



From quantum mechanics a relation could be derived between the range of the nuclear force and the mass of this mesonic quantum. Long before the mesons were found, physicists knew that their mass would have to be around 100 MeV in order to give the correct range of force.

In the late 1930s, several groups of physicists actually found mesons of about the right mass by studying cosmic radiation; mesons are one component of this radiation. Soon it became clear that this was the wrong meson. Although it had the right mass to be Yukawa's quantum* it clearly did not have strong interactions with nucleons. This early meson penetrated matter with the greatest of ease while Yukawa's strongly interacting meson would have been stopped by even the thinnest target material.

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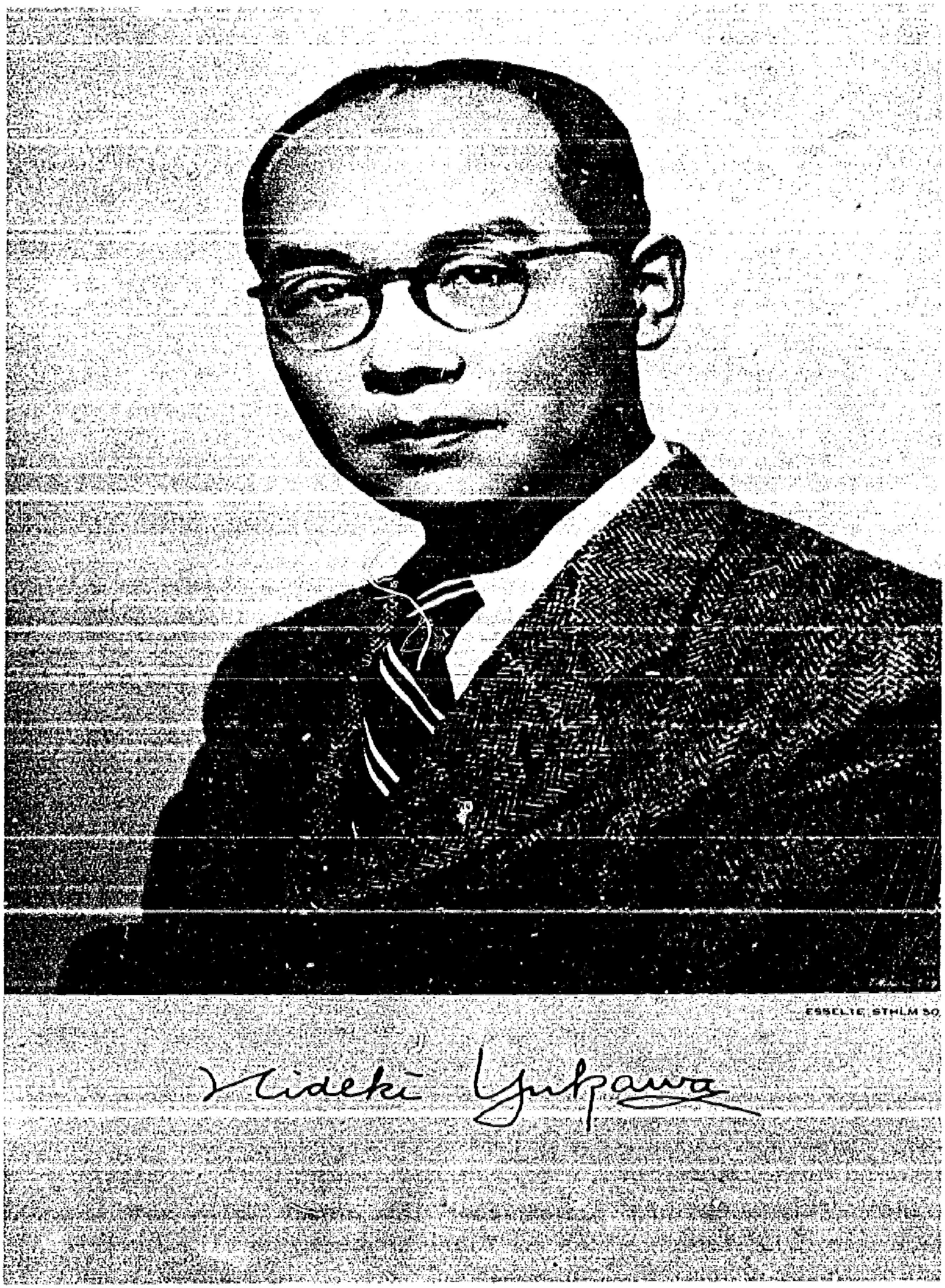
*The best value for its mass is now given as 105.669 ± 0.002 MeV.


ESSELTE STHLM 50
Hideki Yukawa

This early meson, which we now call the mu-meson or muon, behaves like a heavy electron. It has spin ½ and comes in two varieties, μ^+ and μ^-, with equal and opposite electric charges that are equal in magnitude to the charge of the electron. However, the muon is unstable. It decays with a lifetime of about 2.2×10^{-6} second. After a good deal of study, experimental physicists concluded that this decay was of the form

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \overline{\nu}$$

i.e., the muon decays into an electron of the appropriate charge and a neutrino and antineutrino. At this point the reader who has been suitably impressed by lepton number conservation may object. Hasn't it been violated in this decay since the neutrino and antineutrino numbers cancel and leave the electron or positron number? This is easily dealt with by assigning the muon a lepton number in analogy to the electron assignments; the μ^- number is +1 while the μ^+ number is −1. This choice is suggested by the close similarity between the muon and the electron and, as we will see, is confirmed by experiment.

However, the muon doesn't do much for Yukawa's idea. It was not until physicists came back to their laboratories after the Second World War that the search for Yukawa's meson was begun again. At this point the theoretical physicists R. E. Marshak and Hans A. Bethe made the intriguing suggestion that, in fact, Yukawa's meson was probably in cosmic rays all the time, but had not been seen since it decayed before it got to the experimental apparatus. If one of the decay products were a muon, then it would be easy to understand why the first object to be found was the muon and not Yukawa's particle.

In 1947 C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell found Yukawa's meson in cosmic radiation, and it is now known as the pi-meson or pion. It comes in three charge states $\pi^{\pm}_{0}$, has zero spin, and a mass, for the charged varieties, of 139.579 ± 0.014 MeV. It is indeed unstable and its principle decay mode, for the charged varieties, is the two-body decay

$$\pi^+ \rightarrow \mu^+ + \nu_0 \quad \pi^- \rightarrow \mu^- + \overline{\nu}$$

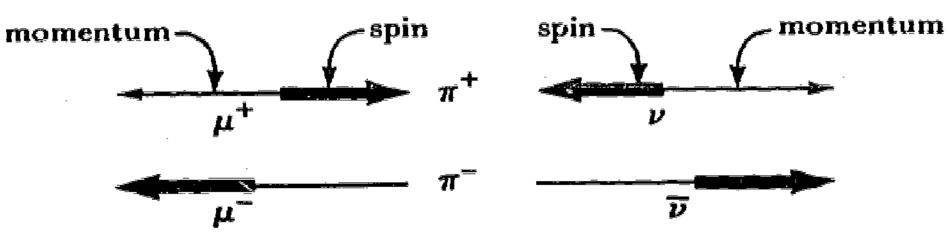
with a lifetime of about 2.6×10^{-8} second. (The neutral pion decays electromagnetically $\pi^0 \rightarrow \gamma + \gamma$ and has a lifetime of only about 10^{-16} second. This reflects the fact that this decay is caused by the electromagnetic forces, which are much stronger than the weak forces that cause the charged pion decay.)

We can now use this information and the conservation of angular momentum to make a very strong prediction about the muons in this decay. From the conservation of lepton number, assigning zero lepton number to the pion since it is a strongly interacting particle, we have the decay schemes for $\pi^{\pm}$

$$\pi^+ \rightarrow \mu^+ + \nu$$

$$\pi^- \rightarrow \mu^- + \overline{\nu}$$

where we have a neutrino or an antineutrino in the final state depending on the charge of the pion. However, the pion has no spin so the total angular momentum of the final state here must also be zero. If the pion decays at rest, with zero momentum, which we can always assume, then the final muon and neutrino must have equal and opposite momentum. Since the neutrino's spin and momentum are correlated we are *forced,* to conserve angular momentum, to have a similar correlation for the muon's spin and momentum. Indeed, we are forced to have:



This situation is summarized by saying that the muons emerging from pion decay are, if the theory is correct, 100% "polarized". This has been thoroughly verified in many experiments and is one of the best confirmations of the correctness of the whole set of ideas presented above about the neutrino.*

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*These pionic experiments were performed in the early 1960s and we would be remiss in not calling attention to a brilliant experiment done in 1958 by the Brookhaven group of M. Goldhaber, L. Grodzins, and A. W. Sunyar. This experiment was designed to measure the helicity of the neutrino emitted in the orginal beta decay from radioactive nuclei. Again it makes use of angular momentum conservation but in a more complex setting than the pionic decay we have described. We will not give details but remark that it firmly proved that this beta decay neutrino had anticorrelated spin and momenta. Thus, there is independent experimental evidence that the neutrinos in ordinary beta decay and in pionic decays have the same helicity.

The Muon and the Conservation Laws

The casual observer might have said that everything was in good order in neutrino land in the early 1960s. However, others, among them Tsung Dao Lee and Chen Ning Yang, the parity people, saw that all was not quite right. In particular, there was one possible decay mode of the muon, which did not seem forbidden by any conservation laws, but which refused to show up.*

$$\mu^{\pm} \rightarrow e^{\pm} + \gamma$$

No example of this mode has ever been seen and a recent limit says that it can occur no more than once in 6 billion of the usual μ decays

$$\mu^{\pm} \rightarrow e^{\pm} + \overline{\nu} + \nu$$

Such a result suggests that there must be some hidden conservation law at work suppressing the decay. It is easy to invent such a law and it is sometimes called the conservation of muon number or the conservation of "muness". We can assign a muon number of +1 for the μ^- and −1 for the μ^+ and insist that if we add the number of muons algebraically before and after a given reaction we must have the same total number. This of course forbids the reaction

$$\mu^{\pm} \rightarrow e^{\pm} + \gamma.$$

To explain that this reaction is forbidden in such an apparently arbitrary way may seem like a joke. However, it becomes much more serious if we ask what the implications are for the regular decay

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \overline{\nu}$$

At the first glance it would seem that we are doomed. We have a muon in the initial state and an electron in the final state so that to be consistent this reaction, which is allowed experimentally, would be forbidden.

However, there is a way out although it looks a little crazy until one gets used to it. We can suppose that there are two kinds of

*It is a rule of thumb in quantum mechanics that any reaction that is not expressly forbidden by some rule will occur at about the same rate as other reactions of the same or similar type.

neutrinos—a muon neutrino and an electron neutrino, ν_μ and ν_e! From this point of view let us consider the conservation of muness and lepton number in the usual mu decay

$$\mu^\pm \rightarrow e^\pm + \nu + \overline{\nu}$$

Let us suppose that the ν which occurs here is the muon neutrino and has a muon number -1. Hence the other $\overline{\nu}$ must be an electron neutrino. Thus the decay scheme should be written

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$

and likewise

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

We could also define an electron number that would be numerically equal to the lepton numbers given above. This number is just the lepton number minus the muon number, and it is also conserved since it is the difference between two conserved quantities.

Particle	Electron number	Muon number	Lepton number
e^-	1	0	1
e^+	-1	0	-1
μ^-	0	1	1
μ^+	0	-1	-1
ν_e	1	0	1
$\overline{\nu}_e$	-1	0	-1
ν_μ	0	1	1
$\overline{\nu}_\mu$	0	-1	-1

Using the assignments above we can now test to see if the decays that we want to be allowed are allowed and the decays that we want to be forbidden are forbidden. In the former category are the pionic decays

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

where we have indicated in the correct neutrino to conserve muness. Among the forbidden decays there is, for example,

$$\mu^- \rightarrow e^- + e^+ + e^-$$

and experiment shows that it takes place at most once in 10 million allowed decays. These confirmations of the conservation of muness are not very direct ones. In the early 1960s, when the conservation of muness and the two-neutrino hypothesis began taking shape a number of physicists, among them B. Pontecorvo of the Soviet Union and M. Schwartz, then of Columbia University, pointed out that the big particle accelerators at CERN in Geneva and at Brookhaven could be used to make a definitive test of these ideas.

The principle underlying these neutrino experiments is simple. A machine like the 33 billion electron volt accelerator at Brookhaven or the 28 BeV at CERN can be regarded as a factory for making high-energy pi-mesons.

The machine accelerates protons and these can be guided by electromagnetic fields so that they strike a target like lithium in concentrated bunches. From these collisions much "debris" in the form of various elementary particles emerges and, in particular, positive and negative pions are produced in the prototypical reactions

$$p + p \rightarrow p + n + \pi^+$$

and

$$p + n \rightarrow p + p + \pi^-$$

These pions can also be focussed into a beam. As the pions move along, they decay into muons, muon neutrinos, and antineutrinos. Because the pions are produced with positive and negative charges in about equal numbers the proton accelerator produces a beam of muon neutrinos and muon antineutrinos in about equal numbers. It is possible to select the sign of the pion charge in the beam by filtering out the other charge electromagnetically so that one can work with either a beam of neutrinos or antineutrinos.

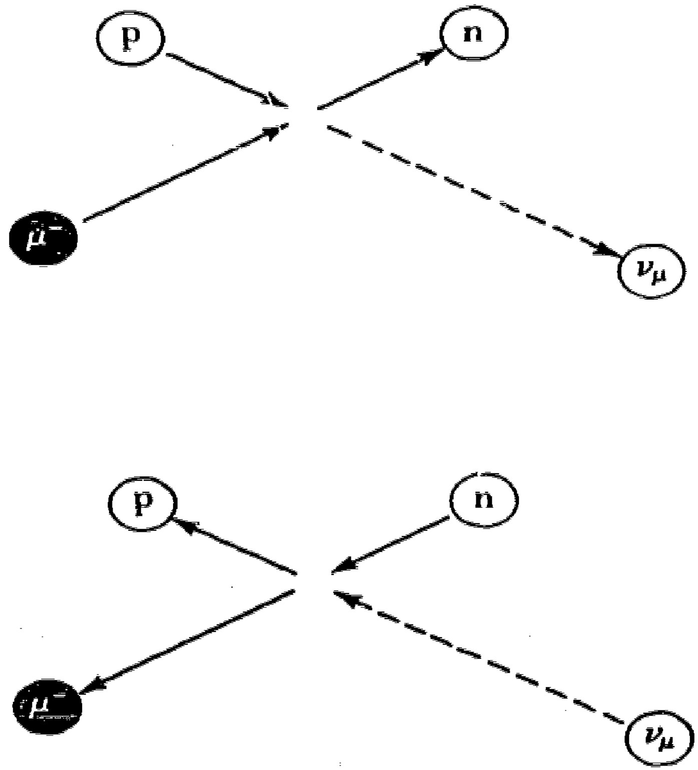
The next step is to watch what happens when these neutrinos strike a target. After the pions decay into muon neutrinos, these neutrinos can have energies that are about 1 BeV or so, because the protons have energies of about 30 BeV. There is plenty of energy in these neutrinos for them to be able to produce muons when they collide with protons, for example, in a reaction like

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

If the conservation of muness is valid there is *no* neutrino reaction initiated by a single muon neutrino or antineutrino from which a single

electron or positron can emerge. In principle, all the experimenter has to do is to see what the ratio of electron-to-muon productions is. This ratio should be zero if muness is conserved. In practice, this is an extremely difficult experiment.

In the first place, the target that the neutrinos hit must be very well shielded. None of the original pions and their decay muons should enter



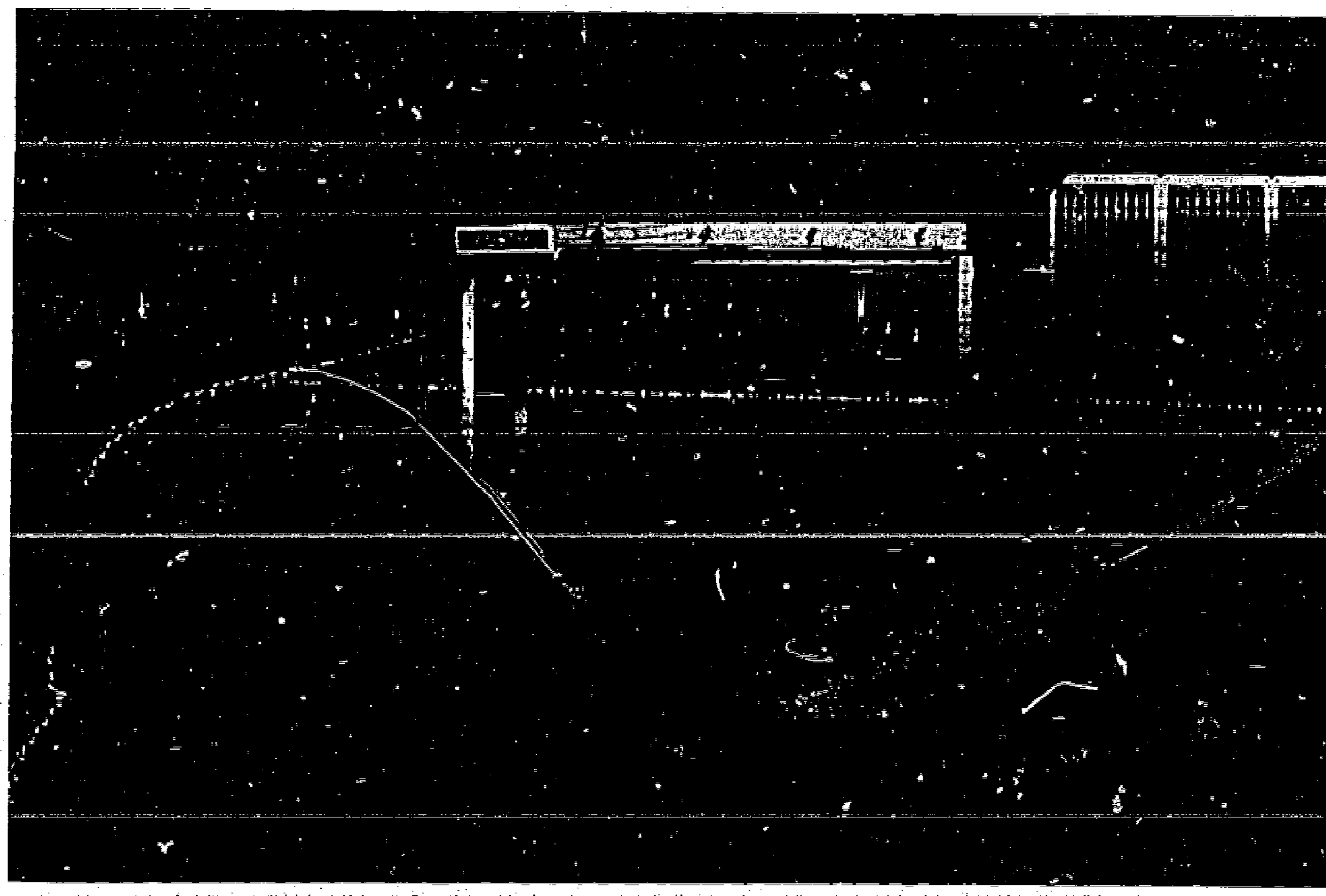
Detection of neutrinos depends on the reversal of a reaction already known to occur. The neutrino leaves no visible tracks in a spark chamber and can only be detected through its interaction with other particles. Since a muon-proton reaction (above) produces a neutron and a neutrino, a visible muon (below) should occasionally appear when a neutron and a neutrino collide.

the target area because they could be confused with the muons, which result from the rare neutrino collisions. A similar difficulty is posed by muons from cosmic rays. Hence there is an enormously complicated shielding problem. In fact, in the Brookhaven experiment, the steel plates from a scrapped Navy cruiser were used to form part of the 44-foot-thick shielding, and the Swiss government supplied the CERN people with similar plates from the strategic steel stockpile that the Swiss have in case the country ever comes under siege. Next there is the question of a suitable neutrino target and muon detector.

The Brookhaven people were able to make use of a then new detection device—the spark chamber—to solve both problems simultaneously. The spark chamber detects the passage of charged particles by observing the sparks they leave when they pass through an arrangement of metal plates. These plates have been charged up so that a spark jumps from one plate to the next when they are disturbed by the passage of a charged particle.

The metal plates are good neutrino targets since they are massive and offer a great many neutrons and protons to the incident neutrinos. The Brookhaven experiment, which was done by a group from Columbia University consisting of L. Lederman, M. Schwartz, J. Steinberger, and many collaborators, made its first results known in 1962. By this time they had accumulated 300 hours, which is a great deal of running time for such a machine experiment.

They estimated that for 3×10^{17} protons accelerated in the machine there were about 10^{14} neutrinos produced. With all the time and all the neutrinos they were only able to identify 29 certain



High energy neutrino interactions in the aluminum spark chamber at Columbia University.

neutrino events. All these produced muons that are readily identifiable in the spark chamber since they leave a characteristically long thin track. Twenty-nine events are not a great many, but it is enough to constitute solid evidence for the conservation of muness.

A year later the CERN group, with an improved experimental set-up that included both spark chambers and bubble chambers,* were able to confirm the Brookhaven results with a substantial increase in the number of events. By 1963 there was no doubt that there were two distinct types of neutrinos.†

This is the surprise that we promised you. But you may not have been so surprised after all if you followed the line of theoretical argument that lead to the prediction of the two neutrinos. Physicists would have been a great deal more surprised if there had been only one neutrino. This is a good illustration of how theoretical prejudices guide and shape the experimental process. As far as anyone knows there is no physical distinction between these neutrinos. They both have spin ½, no charge, and no mass. (The experimental limit on the muon

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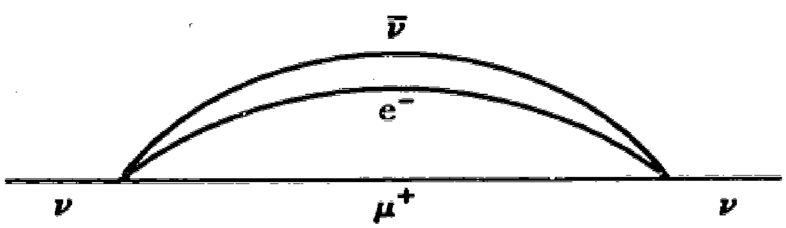
*Liquefied gases that also show tracks of the passage of charged particles.

†In the first section we mentioned that while the neutrino, like the neutron, has no charge it might have a charge structure that arises from the Feynman graph



and others. Such graphs suggest that if there is such a structure it would give a "charge radius" to the neutrino of the order of

$$r_\nu^2 \simeq 10^{-33}\ \text{cm}^2$$

as compared to a charge radius for protons that is approximately

$$r_\nu^2 \simeq 0.66 \times 10^{-26}\ \text{cm}^2$$

In principle, this charge radius can be measured if the neutrinos are allowed to bounce off the protons in a liquefied hydrogen bubble chamber in the reaction $\nu + p \rightarrow \nu + p$. The weak interactions also allow this reaction, but when experiments become very precise, the two effects can be separated in principle, and hence one can look forward to a measurement of the neutrino's charge structure.

neutrino's mass is less than 2.1 MeV. This is not a very good approximation to zero mass, but most physicists would be willing to give high betting odds that the mass is exactly zero.) The only way that muon neutrino differs from its electronic counterpart is that the muon neutrino carries muness. This is a very strange situation and it is quite likely that the muon neutrino may have a few tricks up its sleeve before we have heard the last of it.

We now turn to the role that the electron neutrino plays in astronomy and astrophysics.

TWINKLE, TWINKLE, LITTLE STAR

A colleague of mine once asked himself, "If the weak interactions were switched off, what would be the first large-scale effect noticed by people on earth?" He did not have in mind the fact that a few physicists would find themselves in difficulties with experiments on radioactive nuclei and unstable particles. He was thinking along the lines of the gross effects that would be noticed by everyone. If the strong interactions were turned off, matter would fly apart; if the electromagnetic interactions were turned off, chemical reactions would stop; and if gravity were turned off, we would float off the surface of the earth. His conclusion was rather remarkable. The sun would stop shining and then the stars, one by one, would go out!

As we shall see it is just these weak interactions that help to produce the energy to keep the sun shining. The sun keeps its present size because the force of gravity, which tends to make it collapse, is balanced by the pressure produced by the heated particles in its interior. If these heat processes were turned off, then gravitation would cause the sun to shrink, and it then would heat up more due to the gravitational energy increase. Eventually it would burn itself out. This would take about 30 million years, but we would all have frozen solid, or would have been burned up in the original heating process long before!

Until the late 19th century, the gravitational collapse theory of solar radiation was believed to be the correct explanation of why the sun shone. The trouble began when the process of solar evolution was traced backwards in time.

Theoretically one can enlarge the sun so that it fills the planetary volume to the earth's orbit and then compute how long it would take it to contract to its present size. This is done assuming that it fell at 0.014 cm a minute, which would be enough to account for the radiation presently observed. This time is about 18 million years, which, according to this theory, should be the maximum age of the earth. However collaborative evidence indicates that the age of the earth, at least as a solid body, is between 4 and 5 billion years.

After Einstein's formula for the interconnection between mass and energy, $E = mc^2$, was revealed, it was widely conjectured that this must be the key to the sun's ability to give off so much radiation energy over such a comparatively long time. The problem was to devise some method for converting mass into energy that would work on the scale necessary to keep the sun shining.

In the 1930s the neutron and nuclear reactions, which are processes in which the nuclei are transformed into each other under suitable conditions, were discovered. In such reactions energy is ordinarily given off because the final nuclei are usually less massive than the initial nuclei. Because of the huge c^2 factor, a lot of energy is released. The problem of applying these ideas to the sun is twofold: 1. To find the right nuclear reactions that involve nuclei available in the sun. There is no point in invoking some reactions involving uranium, for example, since there is no uranium in the sun. 2. Defining the "suitable conditions" and making sure that the sun offers these conditions for any reaction that one has invented.

In a typical nuclear reaction one begins with two positively charged nuclei close to each other. (Positively charged since all the stable nuclei have protons in them.) The natural inclination of these nuclei is to repel each other since like charges repel. However if they are pushed so close together that the strong, short-range, nuclear force or the even shorter ranged, weak force can take over, a nuclear reaction can occur.

On earth we accomplish this feat by bouncing one nucleus off another one at great energy in an accelerator, or by making the temperature of the nuclear amalgam hot enough so that in random collisions the nuclei bounce off each other frequently enough to be effective.

A good working temperature for the latter method is about 10 million degrees centigrade. This is a rare temperature on earth, although it is produced artificially in atomic explosions, and perhaps in electron–proton plasmas that have been confined by magnetic fields and heated with electrical discharges.* However, it is a typical temperature for the interior of an average star like the sun. (Red giants are much cooler and white dwarfs are much hotter.†)

As in any good cuisine the nuclear reactions that will cook depend very sensitively on the temperature of the star. There are two excellent reactions for the sun and similar stars. The one that dominates the resultant confection again depends in a crucial way on the temperature. The simplest such reaction was first suggested by C. F. von Weizsacker in 1937. It is a proton collision in which deuterium (heavy hydrogen) is

*See *Controlled Nuclear Fusion,* another booklet in this series.

†Red giants are very young stars with low surface temperature and diameters many times that of the sun. White dwarfs are very old, bluish stars with high surface temperature and a mass close to that of the sun, but which can have a diameter as small as five times the diameter of the earth.

made along with a positron

$$p + p \rightarrow D + e^+ + \nu_e$$

It proceeds via the weak force and out comes the neutrino! The second reaction was proposed about the same time by Hans A. Bethe, and since it is really a series, or cycle of reactions, we give the series as

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^+ + \nu$$

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^+ + \nu$$

$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$$

in which p is the proton, C is carbon, N is nitrogen, and O is oxygen. A remarkable feature of this reaction is that it begins and ends with carbon, and is known as the "carbon cycle". No carbon is consumed and it acts here as a catalyst. In the cycle two neutrinos and three gamma rays are released. These are electron neutrinos. No stars are hot enough so that muons and muon neutrinos are produced. These neutrinos share an energy of about 2 MeV.

In a given star both the Bethe and the von Weizsacker reactions can take place simultaneously in principle. The theory shows that at low stellar temperatures von Weizsacker dominates over Bethe and vice versa at high temperatures. (The crossover temperature between the two reactions is estimated to be about 13 million degrees.) Astrophysicists believe that the von Weizsacker process is the dominant one in the sun. After deuterium is formed in the initial weak process

$$p + p \rightarrow D + e^+ + \nu_e$$

we find some quite interesting results and an experimental prediction.

The newly formed D collides with another proton to produce a light isotope of helium

$$D + p \rightarrow {}^{3}He + \gamma$$

with the release of a photon. Now there are two possibilities. Two heliums can react according to the scheme

$$^{3}He + ^{3}He \rightarrow ^{4}He + p + p$$

or, and this is the interesting case, beryllium can be formed via the process

$$^{4}He + ^{3}He \rightarrow ^{7}Be + \gamma$$

This beryllium can now go into ordinary boron

$$^{7}Be + P \rightarrow ^{8}B + \gamma$$

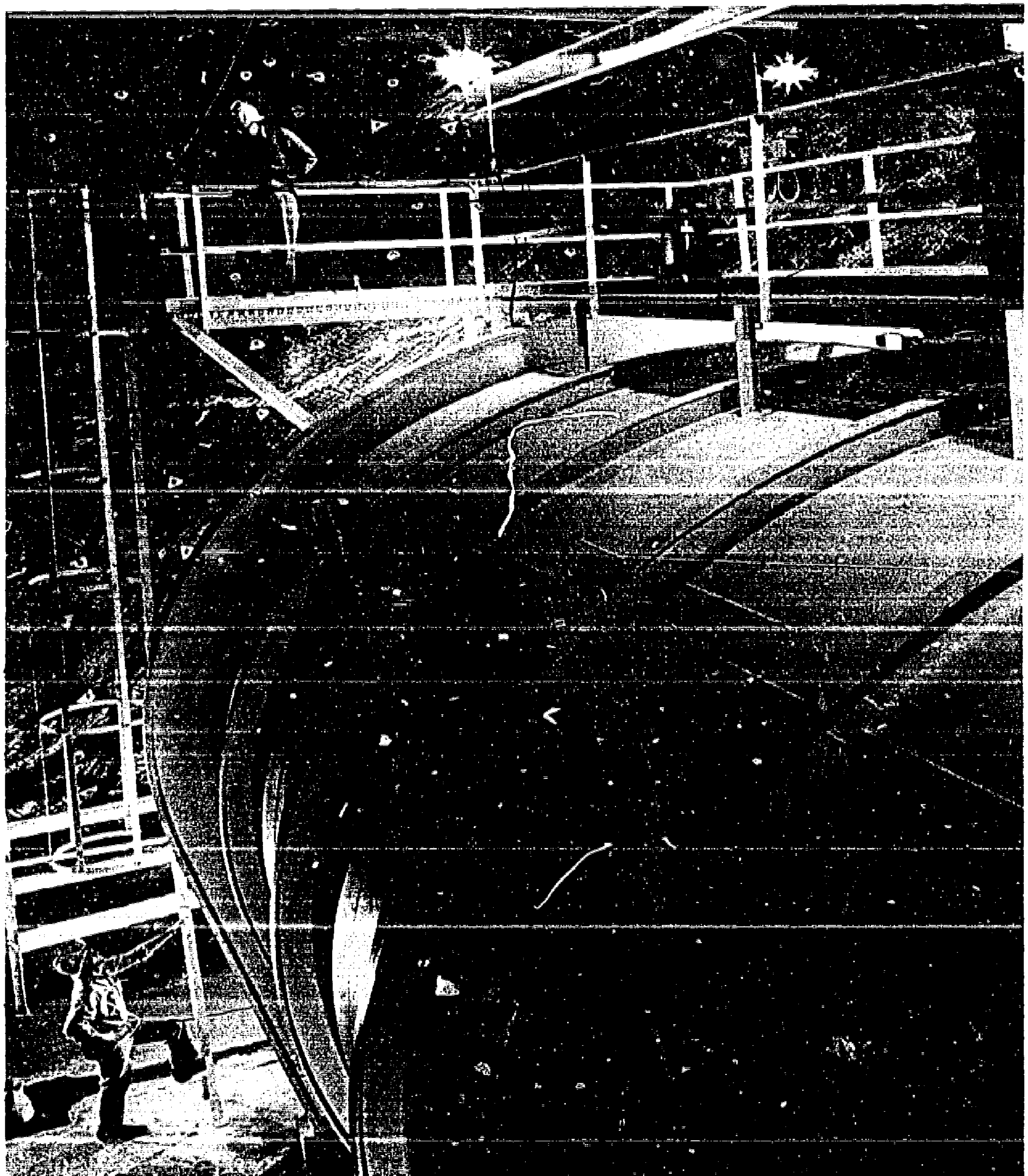
followed by

$$^{8}Be \rightarrow ^{4}He + ^{4}He + e^{+} + \nu_{e}$$

in which Be is beryllium and B is boron. The breakup of ^{8}B into two helium nuclei, a positron, and a neutrino is of special interest since this neutrino has a high energy, 10 MeV. This high energy enables the neutrino to trigger a ^{37}Cl to ^{37}Ar reaction in the same chlorine setup used by Davis to verify the law of lepton number conservation.

For some time Davis has had an apparatus containing 100,000 gallons of perchloroethylene cleaning fluid nearly a mile underground in the Homestake gold mine at Lead, South Dakota. The astrophysical theory of neutrinos would suggest that Davis should have seen some two to seven events a day. But after 159 days of observation, he hasn't seen any. It is still too early to say if this will require some profound change in our ideas about the sun, if there is some fluke in the experimental machinery, or if we have missed something in the weak interaction theory.

It will be of special interest to detect these neutrinos since they come directly from the interior of the sun, whereas sunlight comes from the surface where the temperature is relatively low—10,000 degrees centigrade. A photon that is made deep inside the sun suffers innumerable collisions on its trip to the solar surface. The neutrino, since it interacts rarely, emerges from the depths just as it was made. (It has been estimated that it takes about a million years for a typical photon created in the sun's center to wander to the surface while a neutrino makes the trip in about 3 seconds.)



The Brookhaven solar neutrino detector. The tank is 20 feet in diameter and 48 feet long and contains 100,000 gallons of perchloroethylene. It is located 4850 feet underground in the Homestake Gold Mine at Lead, South Dakota. This detector was designed to observe the solar neutrino flux by the capture of neutrinos to form radioactive argon-37 by the reaction $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$.

The sun is a prolific source of neutrinos. In the time it takes to wink, a trillion (10^{12}) solar neutrinos penetrate your eye. Despite this, solar neutrinos carry only a tenth of solar energy away. Most of the solar energy comes to us in the form of light. There is good reason to believe that in very hot, old stars, which are collapsing and perhaps exploding, this situation may be reversed, and nearly all the energy may be carried away by neutrinos and antineutrinos.

The key reaction is the weak annihilation process

$$e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$$

which usually competes very unfavorably with the electromagnetic process

$$e^+ + e^- \rightarrow \gamma + \gamma$$

There must be electron–positron pairs in the star for either process to work. These pairs are readily formed in the reaction

$$\gamma \rightarrow e^+ + e^-$$

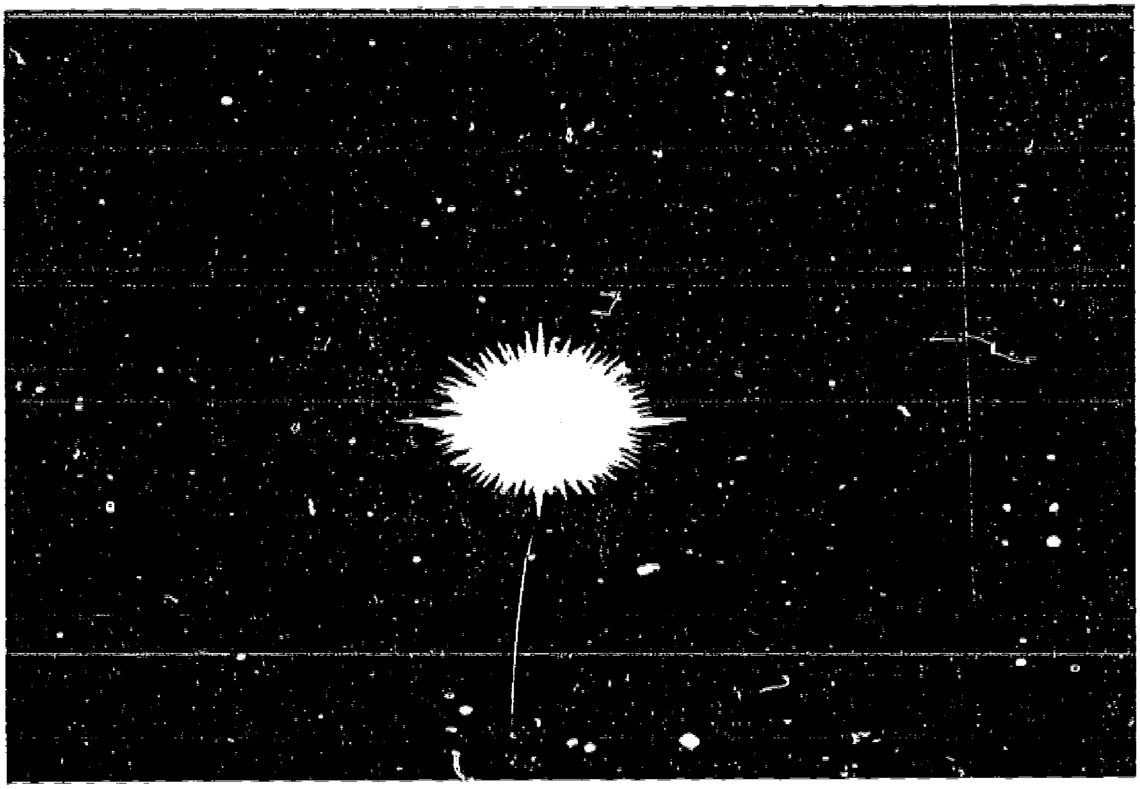
which can take place in the presence of the charged nuclei in the star protons for example. In order for this to happen, the light quantum must have an energy of

$$2\ mc^2 \simeq 1.02\ \mathrm{MeV}$$

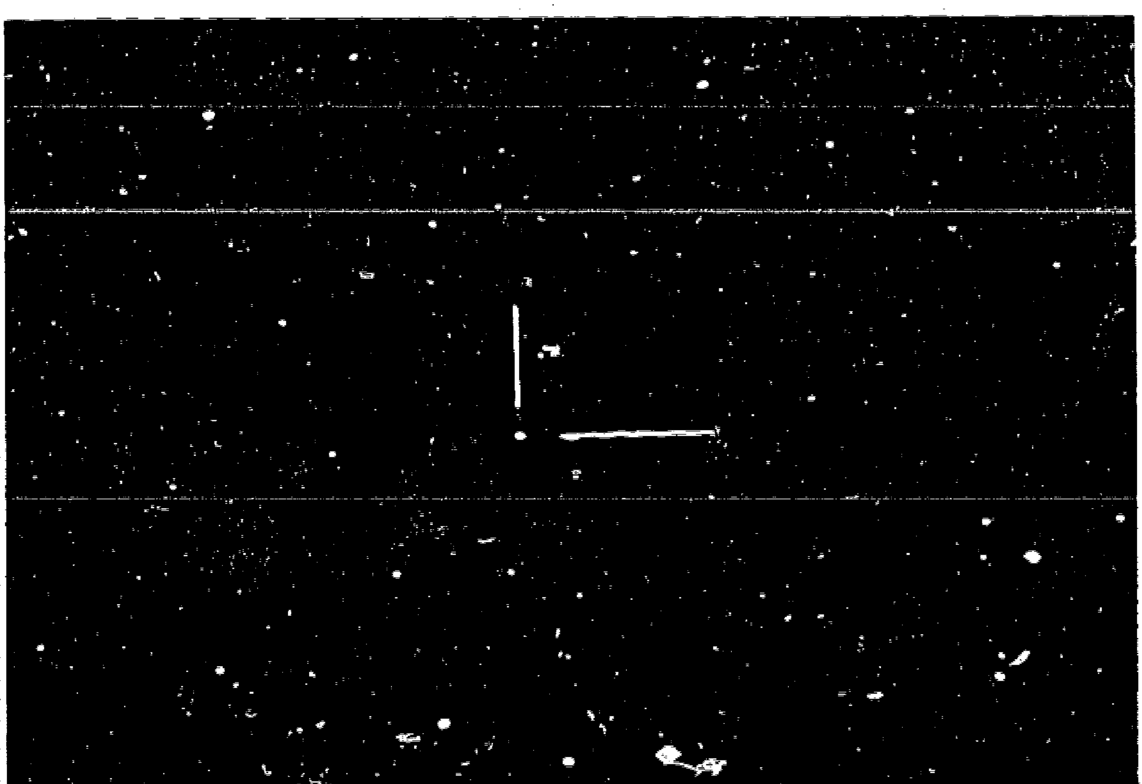
since this is the rest energy of the electron–positron pair.

This photon energy is connected to the temperature of the star 1 eV $\longleftrightarrow$ 11,332° centigrade. To have enough energy to make these pairs, the star must be at a temperature of about 10 billion degrees centigrade. This huge temperature may mark the explosion of an aged star into a supernova with the formation of a white dwarf. Because a white dwarf has a mass close to that of the sun, it is incredibly dense. For example, Sirius B has a density of 375 pounds per cubic centimeter. The last roar of a dying star may be the electron neutrinos made in electron–positron annihilation, which escape from the interior of the star because neutrinos interact so rarely.

There are at least two other sources of astronomical neutrinos that are interesting. For many years, astronomers and physicists have conjectured that there might be neutron stars. If a very dense medium of protons and electrons is squeezed enough by gravitational forces, the



Nova Herculis showing the significant change in brightness between March 10 (above) and May 6, 1935 (below).



electrons can be forced to combine with the protons in the weak reaction

$$e^- + P \rightarrow N + \nu_e$$

a process that is known as electron K capture and which has often been observed in the laboratory. Electron neutrinos are emitted, and under normal circumstances the neutron that is produced would be unstable and it would beta decay. In a very dense environment* two spin-½ particles cannot occupy the same state and there is no unoccupied state for these decay electrons to enter. A dense system of neutrons is formed that may be only a few hundred miles in diameter, but with densities comparable to those of white dwarfs.

Some people believe that pulsars are neutron stars formed by the emission of neutrinos. There is also one school of cosmologists, now the majority, who believe that the present epoch of the universe began with an explosion or "Big Bang", perhaps 10 billion years ago, when all the matter in the universe was collected into a relatively tiny volume. After this explosion, matter and perhaps anti-matter began to expand and fill our cosmic volume. Among the debris from the Big Bang is a certain amount of electromagnetic radiation, which fills the cosmos and which physicists think they now have detected. (Quasars, which are very distant, very energetic, and presumably very old, giant energy sources, may also be part of the early debris.)

In addition there should be a large flux of background neutrinos that date from an epoch close to the original explosion. It would be fascinating to observe this neutrino background and to answer questions such as, "Is there an equal balance between cosmic neutrinos and antineutrinos?" This might help us to understand whether matter and antimatter are balanced in the universe.

Since its prediction by Pauli, the neutrino has been an endless source of surprise and delight to scientists and it would be very satisfying if this extraordinary particle was a clue into the very nature and origins of the universe.

*This is due to a special feature of the quantum theory known as the Pauli exclusion principle.

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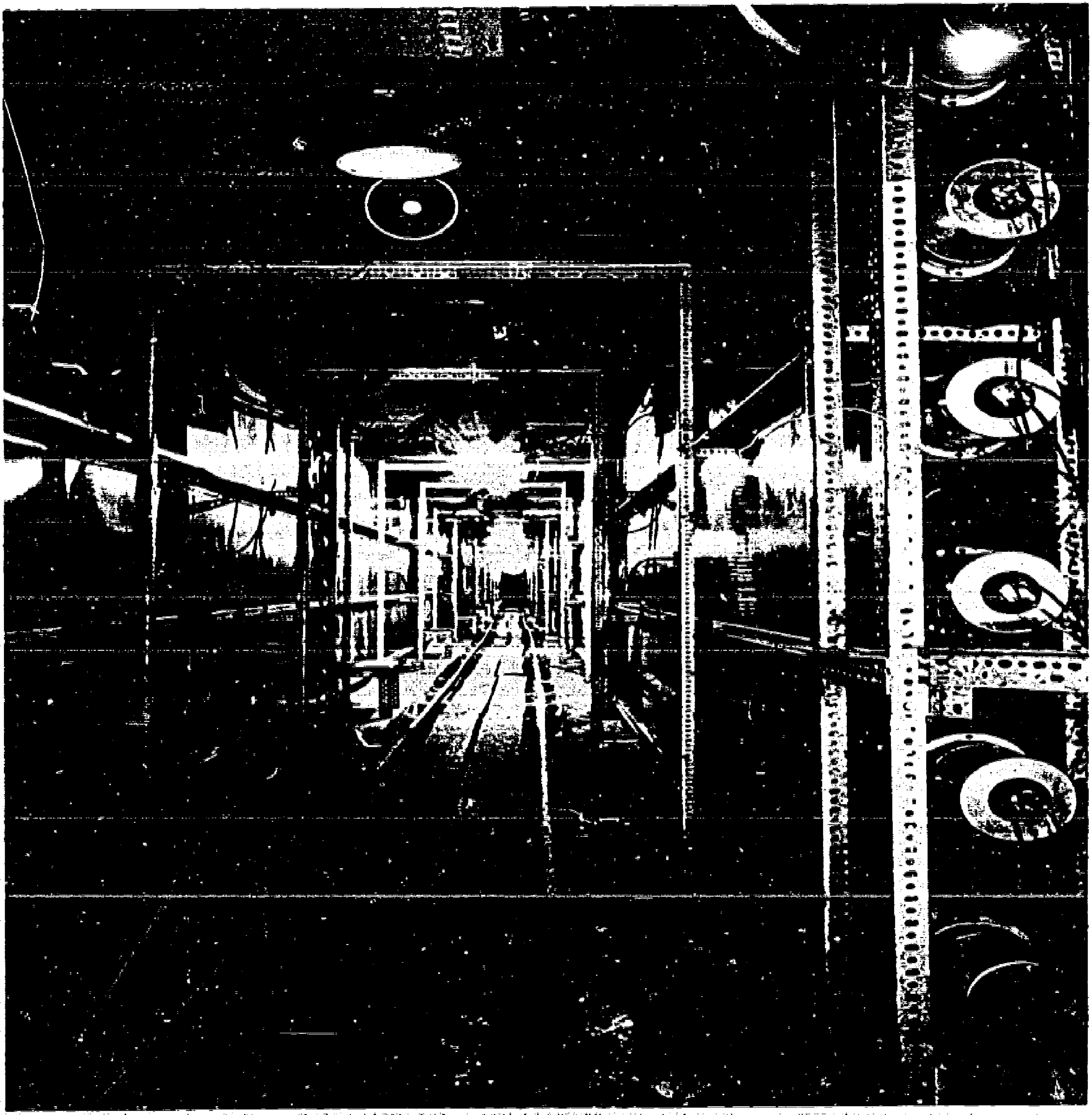

Underground Laboratory for detecting high-energy neutrinos from the atmosphere was hewn out of solid rock at a depth of 10,600 feet in a gold mine operated by the East Rand Proprietary Mines near Johannesburg, South Africa. The detector elements are arrayed in racks along the sides of the 500-foot-long tunnel shown here. At the end of the tunnel is the gold-bearing "reef" that supports the mine. The laboratory has now been superseded by an enlarged and more sophisticated array at a slightly greater depth in the same mine.

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